PALEOMAGNETISM OF TILLITES ON THE AVALON PENINSULA, NEWFOUNDLAND

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by

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ABSTRACT

A paleomagnetic study of the Gaskiers formation, a late Precambrian tillite in the Conception group of eastern Newfoundland, has been completed. 270 hand samples were collected mainly from nineteen horizons within a 300 m continuous exposure at 46.9° N latitude, 53.6° W longitude plus four other areas of well-established geological structure separated by several km laterally and correlated by an uppermost sandy red mudstone layer. A detailed study of 73 representative specimens using AF and thermal demagnetization resulted in a negative fold test and revealed a secondary magnetization stable up to a demagnetizing field of 40 to 50 mT and a demagnetizing temperature of 300 to 400° C. Studies of magnetic properties showed a magnetization having a single Curie temperature of 500 to 600°C borne mainly by magnetite grains having a very broad size range, with some hematite and maghemite also present. Thermal demagnetization to 150°C of 131 specimens from 86 samples and 18 sites in the main exposure resulted in a mean direction of magnetization D = 171°, I = +84° with k = 19, α_{95} = 8°. The corresponding pole position with respect to eastern Newfoundland is 35°N latitude, 51°W longitude with accuracy $\delta_p = \delta_m$ = 16°. The magnetization was likely acquired as a viscous pTRM during prehnite-pumpellyite metamorphism associated with the Acadian orogeny of the Devonian period. A very stable but scattered magnetization possibly of primary origin exists in some specimens as a small proportion of the NRM and sites containing large numbers of these, particularly the red mudstone layer, were eliminated from the pole position determination.

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●	Positive inclinations ("Down")
○	Negative inclinations ("Up")
● (with bar)	Dipole field of earth at sampling locality
+	Present field of earth at sampling locality

CHAPTER I

INTRODUCTION

The main objective of a paleomagnetic study is to find the mean direction and, in some studies, the intensity of one or more components of remanent magnetization in a rock unit and to establish as accurately as possible the time that each component was acquired. From each direction a pole position is calculated for comparison with pole positions from other regions and with pole positions of different ages from the same region to delineate a path of apparent polar wander (APW) for that region.

The study of paleomagnetism is based on knowledge of the history of the earth's field and also provides a great deal of information about this subject which is reviewed along with its relationship to paleomagnetism by Strangway (1970). Some major aspects of the past behaviour of the earth's field are its secular variation, changes in intensity, and reversals of polarity. The secular or slow variation of the field is manifested by small fluctuating non-dipole components and movement of the magnetic poles through about 20° of arc, and averages over about 10^3 or more years such that the field is that of a geocentric dipole aligned along the earth's rotational axis. A paleomagnetic pole position can in many instances be considered equivalent to a corresponding antipole since the average time interval between field reversals (about half a million years) is much less than the age of the rock units we are generally concerned with.

A major assumption on which paleomagnetism is based is that the magnetization in a rock unit is stable enough to preserve the direction of the ambient field in which the rock acquired its magnetization. The study of magnetism in rocks comprises a broad field of research described by many workers (e.g. Néel 1955, Nicholls 1955, Stacey and Banerjee 1974, Nagata 1961).

For most rocks on the earth, particularly older rocks, the natural remanent magnetization (NRM) is a sum of two or more components of magnetization each having a different direction, intensity, and age. A rock contains a mixture of magnetic grains having a broad range of magnetic and chemical properties such as coercitivity and blocking temperature, and resistance to oxidation. Generally some coercivity or blocking temperature interval can be identified with a distinct direction of magnetization, since acquisition of a magnetic component under an imposed field direction may be associated with some particular environmental condition leading to formation of the magnetic carriers at a previous time. To isolate different components of magnetization stepwise demagnetization, comprising a major portion of the experiments described in later chapters, is carried out, as well as certain other magnetic tests. The apparatus and methods involved are described by Collinson, Creer, and Runcorn (1967).

Paleomagnetism is most important in contributing to our knowledge of the earth's evolution, providing evidence for the existence of such processes as continental drift and polar wander. Unfortunately these two phenomena cannot be separately identified with paleomagnetic evidence alone since they both contribute to a similar form of apparent polar wander. Other fields of interest in which paleomagnetism is useful are structural geology, the hypothesis of the expanding earth, and extraterrestrial studies such as those of meteorites and lunar samples. Irving (1964) and McElhinny (1973) provide excellent overviews of the subject of paleomagnetism.

1.1 Paleomagnetism in the Appalachians

The Appalachian tectonic belt extends 3000 km from Alabama at its southwestern end to the island of Newfoundland in the northeast where it is probably best exposed. This mountainous belt of rocks, deformed or emplaced mostly in the Paleozoic, lies between the Grenville province and Paleozoic cover rocks of the continental interior and the Atlantic margin of North America.

Bullard et al (1965) computed a best fit of the continents about the North Atlantic in the Mesozoic according to the shapes of the 500 fathom contours. This fit is compatible with comparisons of the Appalachians and the Caledonides of Europe as well as other orogenic belts (Kay, 1967; Wynne-Edwards and Hassan, 1970). Evidence that the North Atlantic was once closed in this manner, mainly patterns of magnetic anomalies on the sea floor and discordant apparent polar wander (APW) paths from the surrounding continents, is very compelling. Van der Voo and French (1974), Wells and Verhoogen (1967) and Hospers and Van Andel (1968) showed that the paleomagnetic results are consistent with the fit of Bullard et al. The time of breakup of this configuration is not well known but probably late Permian or Mesozoic.

Paleomagnetic studies in the Appalachians have particular importance in demonstrating whether the Appalachians represent the remnants of a proto-Atlantic ocean as suggested by Wilson (1966) on the basis of geology and early Paleozoic faunal distributions. McKerrow and Ziegler (1972) proposed that certain orogenic sutures are the result of continental collisions and favour suturing of the Appalachians in the Devonian, with the Acadian orogeny in the Devonian resulting from the collision of the Canadian and Baltic shields. Morris (1976) and Roy (1972) suggested that parts of western Europe moved northward during the Devonian and approximately into the configuration of the Bullard fit by the end of the Devonian. Kent and Opdyke (1978) suggested that paleomagnetic evidence indicates the southeastern parts of the Maritime provinces and New England were separate from cratonic North America sometime during the Paleozoic and relative motion occurred between these regions until the late Carboniferous. They proposed that the regional folding and metamorphism of the Acadian orogeny resulted from closing of the protoAtlantic, but suturing was not complete until 1500 km of left lateral shear movement took place, bringing the APW paths together. Paleomagnetic data from Newfoundland was not included in their argument due to additional complexities.

An important problem in Appalachian tectonics is the possibility of oroclinal deformation (Carey, 1955) which refers to large-scale bending in the horizontal plane of a previously formed rectilinear feature. Rankin (1976) proposed that the salients and recesses in the Appalachian south of the latitude of Quebec City were initiated as triple junctions during the opening of the proto-Atlantic ocean, discounting oroclinal deformation in this region. Pole positions from dikes of late Jurassic age in central Newfoundland agree with those of corresponding ages from other parts of the Appalachians, implying that oroclinal deformation has not occurred in the northern Appalachians since the Jurassic (Deutsch, 1978). But Irving and Opdyke (1965) found paleomagnetic results from Pennsylvania which suggests oroclinal deformation did occur after the Silurian. Therefore it seems that some oroclinal deformation may have occurred in the northern Appalachians between the mid-Paleozoic and Mesozoic periods, although some of the deformity possibly originated during original rifting of the proto-Atlantic.

1.2 Paleomagnetism in Newfoundland

Studies by Rao and Deutsch (1976) and Deutsch and Rao (1977) have shown that pole positions from the Western platform of Newfoundland ranging in age from Grenville to the Ordovician are near mainland North American poles. This result implies that western Newfoundland was part of the North American margin during this period and has not rotated relative to the mainland since the Grenville. Such a conclusion contradicts Wegener's hypothesis that Newfoundland was rotated 30°, a very important consideration in making paleomagnetic comparisons.

However, a recent study of the late Precambrian Long Range dikes which intrude the Grenville basement of western Newfoundland produces a pole position (Pullaiah et al, 1979) thought to have resulted from alteration in the Devonian (see dates by Wanless et al, 1966). This pole position disagrees with poles of similar age from the interior of North America but agrees with some poles from the northeastern Appalachians (see Chapter 7, Table 7 - 1, Figure. 7 - 1). This might suggest that Newfoundland was in two somewhat similar positions in the

Ordovician and after the Devonian periods but was displaced relative to North America during the Devonian into a position similar to some other parts of the Appalchian region. But more data from suitable localities and periods is required to solve the problem, which will be discussed further as it pertains to this study later in the text.

A most important finding in Newfoundland paleomagnetism is that some Ordovician poles from western and eastern Newfoundland are very discordant, compatible with Wilson's hypothesis of a proto-Atlantic ocean (Deutsch and Rao, 1977). An additional complication is that an Ordovician pole position from the southwestern Avalon platform (Kirschvink, 1979) agrees with corresponding mainland and European poles much better than with a pole from the northeastern Avalon platform (Rao, 1970). This discrepancy and the others described illustrate the difficulty of applying paleomagnetism to plate tectonics in the northeastern Appalachians, and in Newfoundland particularly.

1.3 Paleomagnetism of Tillites

Magnetization in sedimentary rocks can be classed into three types depending on its mode of acquisition. Depositional Remanent Magnetization (DRM) is imposed during deposition in water as magnetized particles are aligned by the ambient magnetic field while they settle. Chemical Remanent Magnetization (CRM) is acquired through chemical change of the particles carrying the magnetization or precipitation from a solution. Viscous Remanent Magnetization (VRM) refers to secondary magnetization caused by reorientation of directions of magnetization of unstable particles in a recent magnetic field, or by reheating over long periods of time during metamorphism or burial.

DRM, the only magnetization which is exclusively primary (formed simultaneously with the rock), differs from younger secondary types of magnetization in exhibiting: 1) larger differences between magnetization vectors taken from specimens from different parts of a sample, and between mean magnetization of samples due to heterogeneity; also greater dispersion between the mean magnetizations of horizons due to the contribution of the paleosecular variation; 2) a tendency towards misalignment of the magnetized particles; 3) inclination error due to settling of elongated particles nearly parallel to bedding. CRM is very common in sedimentary rocks and particularly in red horizons. The subject of DRM is discussed by Nagata (1962) and DRM and CRM is red beds is discussed by Collinson (1965, 1974) and by Roy and Park (1972, 1974).

The type of rock used in this study is a Late Precambrian mixtite (Schermerhorn, 1966) which shows various evidence of being a tillite (Bruckner and Anderson, 1971), the nature and identification of which is described by Harland et al (1966). Late Precambrian tillites occur world-wide and have particular importance in paleomagnetism. If they are synchronous, glacial conditions must have occurred at low latitudes and they would thus represent a chronostratigraphic marker horizon. Williams (1975) has attributed tillites to increased obliquity of the ecliptic which causes increased seasonal weather changes world-wide.

It has been shown by Gravenor et al (1973) that a DRM occurs in the basal clay till of recent glaciers. It is well known that iron-bearing sediments settling in water will form a DRM and thus it may be expected that useful paleomagnetic results may be obtained from a tillite deposited at the base of a glacier or from floating ice in a marine environment. Geological processes in large-scale present-day glacial environments are described by Chriss and Frakes (1977) as well as many others. Young (1976) discusses another Precambrian formation of glacial origin, the Rapitan Group, which was subjected to paleomagnetic study by Morris (1977).

Harland (1964) proposed a world-wide Late Precambrian glaciation based on geological evidence. Crawford and Daily (1971) and McElhinny et al (1974) suggested that the widespread occurrence of the tillites is due to polar wander. Tarling (1974) reported a low-latitude magnetization from Eocambrian Tillite in Scotland which he concluded was primary but no fold test (Graham, 1949) was possible due to uniform tilting of the beds. According to Morris (1977) most paleomagnetic results from Late Precambrian Tilliates are inconclusive since both shallow and steeply inclined remanence directions were found, neither of which could definitely be established as a primary magnetization. It can be said that the synchroneity or diachroneity of late Precambrian tillite deposition is at present unresolved, and paleomagnetic data from any tillite, if it can be shown to be of primary origin, will contribute significantly to the solution of this problem.

1.4 Objective of Study

The objective of this study is to find the mean directions and pole positions of one or more components of magnetization of the Gaskiers Formation. Additionally it may be established whether each magnetization was acquired before or after folding and possibly whether it is primary or secondary. If a magnetization is primary the latitude of deposition and thus possible synchroneity of similar horizons in other regions may be inferred. If a magnetization is secondary the pole position obtained would be more useful if the time of acquisition could be found. Then it would add to the sparse supply of paleomagnetic data available in the Appalachians and could be compared with these and other data from the continental cratons.

CHAPTER 2

GEOLOGY AND SAMPLING

2.1 Geology of the Appalachians

The Appalachian tectonic belt comprises an elongated region of rocks emplaced mainly from late Precambrian to Carboniferous times and deformed during the same time span in a series of orogenic episodes. The Appalchians are bounded on the southeast by the Atlantic Ocean and Coastal plain and on the northwest by the Grenville Province of the Canadian Shield partly overlain by Paleozoic sediments. In the Canadian Appalachians the Grenville Province and the orogen are separated by the Logan Fault along the St. Lawrence River and by the Gulf of St. Lawrence. The contribution of Grenville rocks in forming a basement to the Appalachians is uncertain but is possibly of major extent, since Grenville inliers are exposed along the northwest side of the orogen (Rodgers, 1972).

The Newfoundland Appalachians can be divided into three provinces: the Western platform, Central Paleozoic mobile belt, and Avalon platform (Williams, 1964). The platform areas both consist of Precambrian and younger rocks slightly deformed in the Paleozoic, having little else in common with each other. These relatively stable platforms bound the highly metamorphosed and indented mobile belt in which Precambrian rocks are absent. All three provinces are dissimilar except in showing a predominant northeasterly trend in whatever structural features are present such as folds, faults, and schistosity. Details may be seen in the tectonic - lithofacies map of Williams (1978).

After the suggestion of Wilson (1966) that the Appalachians are the site of a proto-Atlantic ocean, the various features of the orogen were interpreted in terms of the expansion of this ocean between the late Precambrian and Ordovician, followed by its contraction ending in the Devonian (e.g. Dewey, 1969; Bird and Dewey, 1970; Kennedy, 1975). But Williams (1979) argues that plate tectonic processes ended in the Ordovician and do not explain subsequent development of the orogen.

The northeastern Appalachians were subjected to three main orogenic episodes during their history: the Avalonian during the late Precambrian, the Taconian during the Ordovician, and the Acadian during the Devonian.

The Avalonian orogeny is better apparent on the Avalon Peninsula of Newfoundland than anywhere in the Appalachians and is marked by intrusion of the Holyrood granitic pluton with associated deposition of pyroclastic rocks in some places mixed with other sediments. This is interpreted by Hughes (1972) as evidence for formation of an elongate volcanic island belt through calc-alkaline volcanism followed by erosion, possibly on the northwestern margin of ancient Euro-Africa. Compressional features are absent but were imposed later, probably in the Devonian period (Hughes, 1970).

Deformation and plutonism in the middle to upper Ordovician is widespread in the Appalachians. Taconian deformation is easily apparent in north-central and western Newfoundland as an unconformity but evidence is lacking further southeast (Rodgers, 1967).

The Acadian deformation represents the climactic event affecting the Newfoundland Appalachians causing the majority of the metamorphism and plutonism in the northeastern Appalachians (Williams, 1969). Radiometric ages of granitic bodies and plutons in central Newfoundland range from 315 to 510 Ma but most of these are 400 Ma or younger (Bell and Blenkinsop, 1975). The Acadian was associated with compressional features and shortening across the system as evidenced by upright folds, in contrast with recumbent structures reflecting horizontal transport during the Taconic Orogeny (Williams, 1979).

In the southern maritime provinces orogeny was spasmodic from the middle Devonian to early Permian. The Alleghenian movement in the Carboniferous and Permian is best recognized in New Brunswick and Nova Scotia. A maximum marine transgression in the Mississippian is a convenient dividing line between the Acadian and the Alleghenian (Rodgers, 1967). Lack of younger rocks in southeastern Newfoundland makes the record of movements later than the Acadian unclear.

Unaltered Triassic diabase was found in three places along an aeromagnetic lineament trending east-northeast in the southeast Avalon Peninsula (Papezik et al, 1975; Hodych and Hayatsu, 1979). Like the Jurassic lamprophyres in central Newfoundland this is probably a tensional feature related to the opening of the present Atlantic Ocean.

Excepting these small features no deformation occurred in the northeastern Appalachians since the Alleghenian except for gradual uplift and erosion. It is improbable that any major deformation took place in eastern Newfoundland since the Acadian orogeny of the Devonian. Thus, it is not expected that any stable magnetization acquired at any time later than the Devonian will be observed.

2.2 Geology of the Avalon Peninsula

The geology of the Avalon Zone of Newfoundland is a controversial and in many ways poorly understood subject described and debated more recently by King (1979), Williams and King (1976), Hughes and Bruckner (1972), Kennedy (1976), and Blackwood and Kennedy (1975) as well as others listed in the following discussion. The Avalon Peninsula is mainly composed of a core of Precambrian volcanic rocks partly interbedded with and surrounded by late Precambrian and Cambro-Ordovician sediments (Fig. 2 - 1). Exposed centrally in the peninsula is the Harbour Main Group consisting of a minimum of 2000 meters of subaerial volcanic rocks. Intruding this with local deformation is the Holyrood plutonic series outcropping over 500 km^2. About 2000 meters of marine sediments including shales, siltstones, greywackes, and subaerial volcanic rocks, comprising the Conception Group, appear to overlie the Harbour Main with a contact appearing at various places both conformable and unconformable with some interbedding. The Gaskiers Formation, a Precambrian tillite which is the subject of this study, is contained near the base of the Conception Group.

All of the above are exposed in a horst-like belt bounded by north-south trending faults and surrounded by thick sedimentary basins. Exposed at the base of these is the Conception Group, overlain in the west by the 3000 meter Hodgewater Group and in the east by the equivalent Cabot Group, a series of shales, sandstones, and conglomerates whose highest beds have been removed by erosion. The Hodgewater Group is covered by the Random Formation, a white quartzite, which is overlain by lower Cambrian beds exposed southeast of Trinity Bay and on the

FIGURE 2-1

GEOLOGY OF EASTERN NEWFOUNDLAND

LEGEND

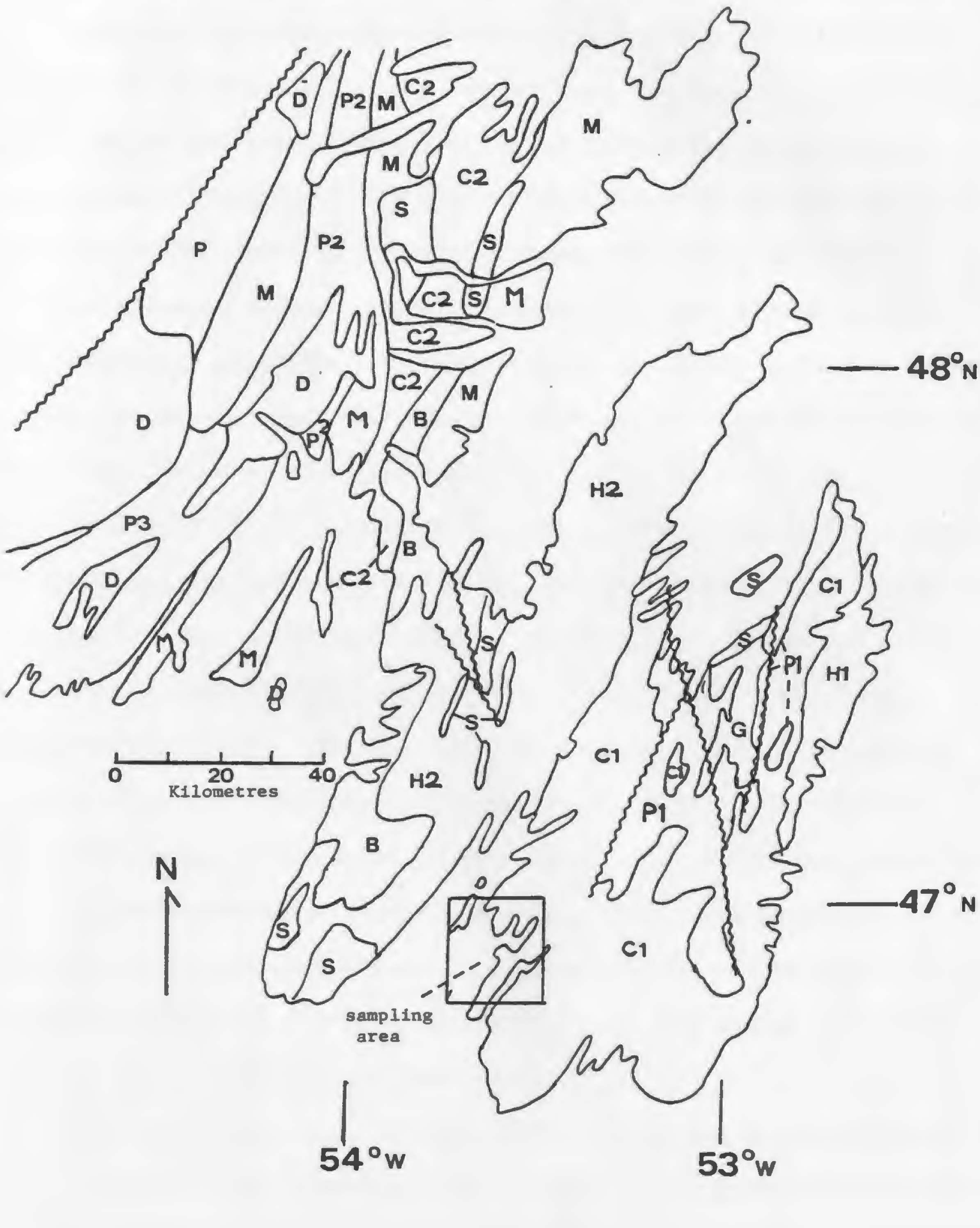
D	Devonian pluton
S	Cambro-Ordovician sediments
H1	Cabot Group
H2	Hodgewater Group
M	Musgravetown Group
C1	Conception Group
C2	Connecting Point Group
G	Holyrood Granite
P1	Harbour Main Group
P2	Love Cove Group
P3	Burin Group

Listed in order of increasing age (except equivalents)

Precambrian unless designated otherwise

Fault

FIGURE 2-1 : GEOLOGY OF EASTERN NEWFOUNDLAND



southwestern Avalon Peninsula. An undeformed flat-lying marine Cambro-Ordovician sequence bounds the volcanic rocks to the north.

There is some dispute concerning the relationship of these sediments to the Holyrood granite which seems younger than the estimated age of most of the Conception Group which at its top contains soft-bodied metazoan fossils of age 610 to 630 Ma exposed at Mistaken Point (Anderson, 1972). But the Conception Group including the Gaskiers Formation contains volcanic detritus whose apparent source is the Holyrood pluton. According to McCartney et al (1966) the Rb-Sr isochron age of the latter is 574 ± 11 Ma, but Frith and Poole (1972) revised the age to 607 Ma based on revision of the Rb decay constant from 1.47×10^{-11}/yr to 1.39×10^{-11}/yr. The decay constant is still in dispute but the preferred value is now 1.92×10^{-11}/yr (Steiger and Jager, 1977) which would give an age of 586 Ma. It is possible that the granite was intruded in pulses, the isochron age giving the time of the last intrusion. A point of view favoured by Anderson (1972) is that volcanics in surrounding sediments may have originated in older unknown granites and the Holyrood pluton was intruded toward the close of Conception Group deposition. But Hughes and Bruckner (1971) and Hughes (1972) propose a model in which the Harbour Main and Conception Groups are contemporaneous alluvial and marine facies respectively of an island arc environment.

Of utmost importance to this study is the age of the folding in the sampling area since a fold test (Graham, 1949) determines whether the magnetization of the tillite was acquired before or after folding.

As discussed above the two main deformations affecting the Avalon Peninsula are the Avalonian of the late Precambrian and the Acadian of the Devonian, therefore the folding is assumed to have occurred during one of these periods.

A view shared by many authors, including Hughes (1970), Poole (1967), and Williams (1969) is that the northeast-trending open folds on the Avalon Peninsula are the result of the Acadian orogeny. Cambrian rocks exposed southeast of Trinity Bay are evidence of this because they show a similar style of deformation to that occurring in underlying Precambrian rocks. These folds are similar to and nearly continuous with the upright open folding in the area on the east side of St. Mary's Bay where the Gaskiers formation is exposed. This evidence suggests that the folds in the Gaskiers Formation are younger than the Cambrian and not associated with the Avalonian orogeny.

An objection to this view is that the Cambro-Ordovician rocks of Bell Island and southern Conception Bay are undeformed, but this is interpreted as being due to protection by underlying batholithic rocks (Hughes, 1970).

A large portion of the Avalon Peninsula was subjected to subgreenschist metamorphism mostly of prehnite-pumpellyite grade and probably of Acadian age (Papezik, 1974). Devonian ages were found by Stukas (1977) in Harbour Main and Love Cove Groups and the Bull Arm Formation by the AR^{40} -AR^{37} method and also by Hussey (1979) in the Love Cove Group, supporting the contention that the metamorphism is Acadian. Higher metamorphism is seen in a thermal aureole around the Holyrood granite. Further details concerning these disturbances in eastern

Newfoundland will be discussed as they pertain to the paleomagnetism of the Gaskiers Formation in Chapter 7. But it may be stated here that there is a strong probability of observing a magnetization acquired during the Acadian orogeny of the Devonian.

The geology and development of the Avalon Zone in Newfoundland can be extended to other exposures of this zone in New Brunswick, Nova Scotia, and the British Isles as described by Rast et al (1975). Comparisons of the Avalon Zone with northwestern Africa are provided by Bruckner et al (1977) and Hughes (1972). As was discussed in Chapter 1, any paleomagnetic data from the Avalon Zone is ultimately linked to the tectonic history of wide-ranging rock units from the margins of the proto-Atlantic ocean.

2.3 The Gaskiers Formation

The sedimentology and geological setting of the Gaskiers Formation are described by King (1977) and King and Williams (1977). A paleomagnetic study of the Gaskiers Formation is the subject of this thesis.

The formation is a 300 meter thick sequence of till-like beds and stratified sediments including rhythmites, mixtites, and disrupted and contorted sandstones. Evidence of glacial origin is provided by faceted and striated clasts, but no underlying striated basement is present. The top is well-defined in all the exposures sampled by red mudstone and red mixtite. In some of the beds turbidity currents, folding, and décollement are present. According to King (1977) some beds were probably deposited by floating ice in a marine shelf environment with pyroclastic rocks also present.

Estimates of thickness and sedimentation rates show an age of 670 to 715 Myr. for the Gaskiers Formation (Anderson, 1972). The tillites are well correlated with those elsewhere, particularly those in the Dalradian of the British Isles which have a very similar geological setting. The Dalradian has been dated by the Rb-Sr method and the age of the tillites there is estimated at 695 Myr. in very good agreement with the Gaskiers Formation. The tillite is provisionally correlated with those in central Australia and those in the Rybachiy Peninsula, U.S.S.R. (Anderson, 1972).

2.4 Distribution of Sampling

2.4.1 Sampling Scheme by area

Figure 2 - 2 shows the sampling areas labelled by capital letters on the shoreline of St. Mary's Bay where the Gaskiers Formation is best exposed. The structural dip throughout all areas is about 45° but the strikes vary from about 20° for areas D, G, and F to 60° for area C and 200° for area L since the formation is exposed on the limbs of an adjacent syncline and anticline (using the convention dip direction = strike + 90°).

A total of 271 hand samples were collected, the majority (165) of which were taken from the most easily accessible area, Double Road Point, labelled D. The other areas were much more structurally distorted especially in the lower horizons but these were sampled in order to perform a fold test (Graham, 1949) and avoid misinterpretation of locally anomalous results. Directions of magnetization taken from

FIGURE 2-2

EXPOSURES OF THE GASKIERS FORMATION ON ST. MARY'S BAY

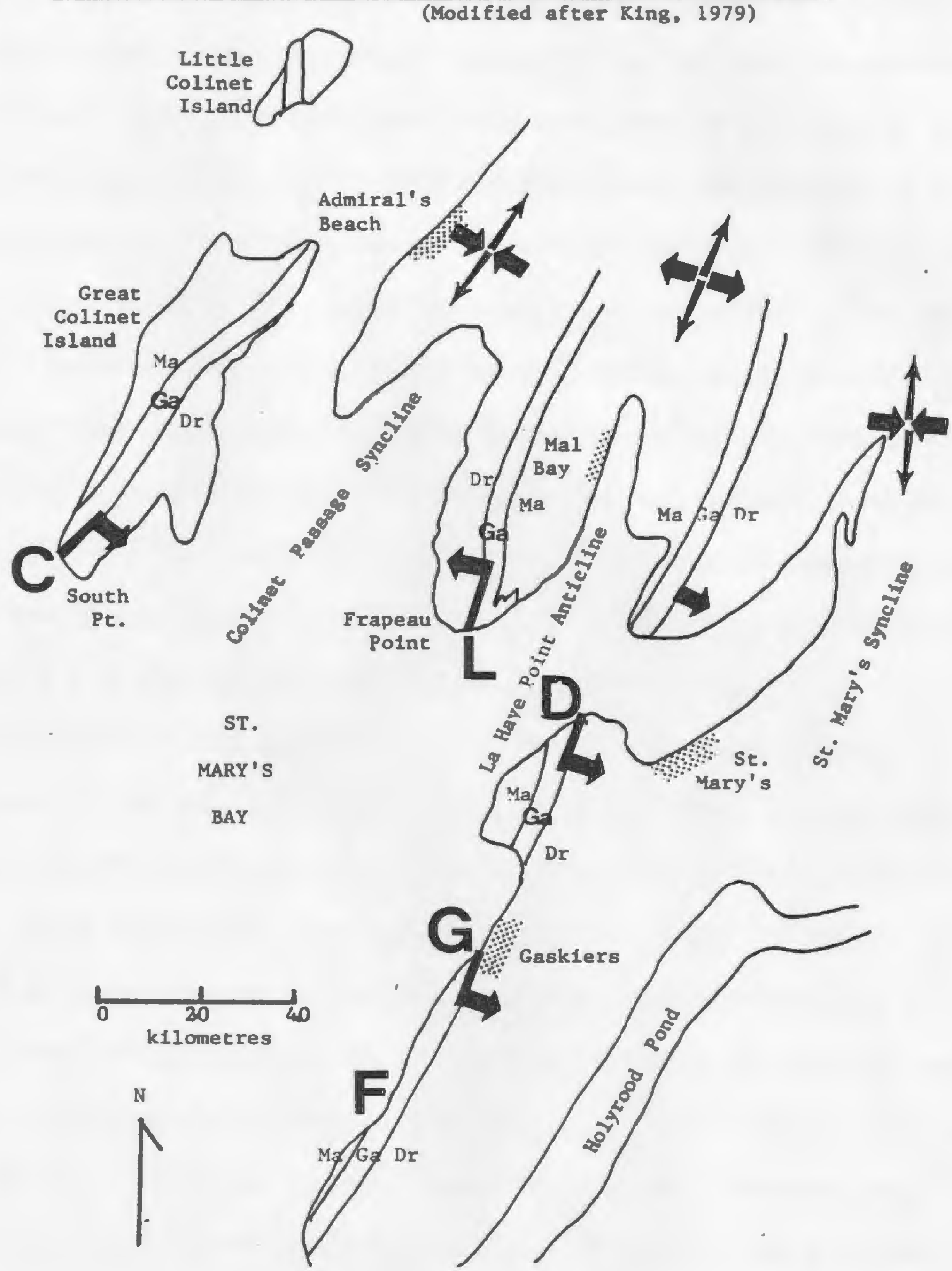
LEGEND

Ga	Gaskiers Formation (mostly unexposed inland)
Ma	Mall Bay Formation (mostly unexposed inland)
Dr	Drook Formation
	Uppermost sandy red mudstone layer in sampling areas
	Direction of dip

Sampling Areas:

D	Double Road Point
G	Gaskiers
F	False Cape
C	Great Colinet Island, South Point
L	Long Point (near Frapeau Point)

FIGURE 2-2 : EXPOSURES OF GASKIERS FORMATION ON ST. MARY'S BAY
(Modified after King, 1979)



sites with bedding plane orientations different by an appreciable amount can help establish whether the magnetization was acquired before or after these orientations diverged, assuming the bedding planes were once parallel. If the directions agree best before correction for bedding tilt they were most likely acquired after folding of the bedding planes. If the directions agree significantly better after correction for bedding tilt they were probably acquired before folding. This would indicate a magnetization of very great stability which may be primary, that is, acquired during emplacement of the rock unit.

In each area the number of samples was determined largely by accessibility and was particularly small in the areas accessible only by boat, the South Point of Great Colinet Island (C) and Long Point (L) which yielded 21 and 15 samples respectively.

From the town of Gaskiers (area G) southward the strike is nearly parallel to the shoreline and the stratigraphy is not clear, and therefore, despite easy accessibility only 40 samples were taken from here. At area F only one sample was taken from each of nearly 30 distinct horizons because of difficult access and distortions of the bedding, which also occurred in the southerly parts of area G, with some faulting. The samples from area F were not later studied, since in the type of analysis employed several samples from each horizon were required, and there were sufficient numbers of these from other widespread areas.

2.4.2 Sampling scheme by horizon

It is important to note here the convention used throughout this text for the terms "site" and "horizon". Where emphasis is not required these terms are used interchangeably although they are intended to have slightly different meanings. In a paleomagnetic study "site" usually refers to a mechanically intact sampling locality where the same bedding tilt measurements apply throughout. Here "site" indicates the horizon as well as the area in which it occurs, since certain horizons and particularly the uppermost layer occur in several areas. "Horizon" is used in a context where the area being discussed is understood; e.g. Horizons 1 to 16 occur only in area D. Bedding orientations and sampling horizon descriptions are listed in Table 2-1. Some samples were taken in a continuous vertical sequence, about one every 5 or 10 meters throughout area, and fewer in other areas, but it was later decided that these would not be necessary in the experiments. The important part of the collection came from 26 horizons, including two which were not used for pilot studies, counting the top horizon separately in the four different areas. Between three and seven samples from each of these, taken as close as possible to a single plane parallel to the bedding, were used for laboratory work. These 26 horizons appear in 13 sites, numbering between one and eight per site. Nineteen horizons in seven sites were the best defined and least contorted thinner beds at Double Road Point.

In area C two horizons, the upper consisting of two thin and closely spaced beds, appear in one broad site, containing the red mudstone above and below the South Point Member, a purple agglomerate and tuff layer with some sandstone, siltstone, and mudstone occurring in area C only. This could not be sampled due to lack of bedding and

TABLE 2 - 1

Sampling horizons and bedding orientation

Area	Interval	Horizon	Description of bed containing sampling horizon	Depth ** (m)	Locality	Strike Value +	Strike Accuracy *	Dip Value	Dip Accuracy *	Number of Determination
D	5m.	1	mixtite							
		2	reddish mudstone, dropstones							
		3	sandstone, dropstones							
		4	reddish sandstone, dropstones	275	a	24	3	42	3	13
		5	laminated mudstone			<u>24</u>	2			5
		6	laminated mudstone							
		7	laminated sandstone, dropstones							
		8	contorted mixttite, sandstone							
	Fault									
		9	disrupted bed	225	b	23	4	47	3	4
	½m.	10	rhythmite	215	c	14	4	42	4	4
		11	sandstone							
	1m.	12	laminated sandstone	190	d	9	4	46	10	4
		13	sandstone, dropstones			8				1
	3m.	14	mixtite below conglomerate	160	e	25	6	42	9	6
		15	mixtite above conglomerate							
	Fault									
		16	thin laminated siltstone, dropstones	30	f	22	4	52	8	6
	½m.	17	mixtite (massive)	3						
		18	red mudstone and mixtite		g	23		50		1
		19	red sandy mudstone, dropstones	0						
G		18	slumped reddish sandstone	100	h	22	6	42	5	4
	Fault									
		19	same as D-19	0	i	17	7	48	6	11
						<u>19</u>	6			3
C	20m.	19	similar to D-19 with tuff		j	59	1	43	1	2
		20	red mudstone			<u>59</u>	1			2
L		17	mixtite	50	k	174	7	23	3	5
	Fault									
		18	coarse sandstone	40	l	164	11	36	7	6
	Fault									
		19	same as D-19	0	m	<u>198</u>	7	40	6	6

\+ Underlined values taken by sun compass

* One-half of difference between max. and min. values

** Stratigraphic estimate from top of formation jointing, and drilling would be difficult due to inaccessibility. Two sites containing the top horizon and one lower horizon of uncertain stratigraphic position were sampled in area G. Three horizons occur at the only westerly-dipping exposure, at Long Point. The two lower horizons here were used for NRM measurements but not for demagnetization due to poor sampling characteristics, i.e. lack of a well-defined bedding plane from which accurately oriented samples could be taken.

2.5 Sampling technique

2.5.1 Method

Samples were oriented prior to removal from their in-site positions as follows. The horizontal plane was marked on two faces of the sample as near as possible to vertical and mutually perpendicular, using a level. The bearing of one of these was found with a Brunton magnetic compass, and corrected for the present magnetic declination.

The strike and dip of the bedding plane at each site was taken either by magnetic compass or a solar compass. These were frequently compared on sunny days by taking the bearing of a flat surface in the same material as that being sampled with both instruments. The difference was never greater than 2° and this serves as a check for all measurements taken by the Brunton compass to ensure against errors induced by rock magnetization. The solar compass could not be used extensively due to lack of sunshine in the area. In any case the intensity of remanence and susceptibilities of all samples measured were low, therefore any influence of rock magnetization on compass readings is unlikely.

2.5.2 Orientation errors

Errors in orientation of samples and specimens are significant but reduced by the technique of cutting two or more specimens from each sample and averaging their magnetic directions as well as those from different samples within a horizon.

The accuracy of orientation of a sample is estimated at within two to five degrees depending on flatness of the faces on which orientation marks are made. Between one and three cores were cut from each sample and one to three specimens were cut from each of these. The cores are indicated by numbers (1, 2, or 3) and the specimens by capital letters (A, B, or C) to indicate relative proximity of specimens within a sample. The sample orientation marks are transferred to the specimens with an accuracy estimated at within two or three degrees. In practise dispersion of magnetic directions of different specimens within a sample is greater than that expected from orientation errors alone since heterogeneity of a sample is a large effect. This is expected to be particularly large in tillite since most samples contain small dropstones some of which, being of pyroclastic origin, may be strongly magnetized. Horizons and samples containing obvious large dropstones were avoided during collection.

Accuracy of strike and dip measurements varies greatly from one site to another, since some sites have better defined bedding planes than others and in some places the beds are curved. Generally more and better measurements were taken where more samples were taken since ease of hand sampling increases as the extent and number of flat beds increases. For optimum accuracy a number of measurements, between 3 and 10 or more, were taken at each site to average out error in measurement and curvature of bedding.

CHAPTER 3

NATURAL REMANENT MAGNETIZATION (NRM)

3.1 Measurement of NRM

Directions of NRM and magnetic moments of all specimens and samples from 26 sites were measured, usually within a few weeks of coring of the sample but after various periods of storage of whole samples, up to a few months. Individual specimens were stored with their bearing marks pointing approximately horizontally westward (magnetic) and with the axis normal to their top surfaces pointing toward magnetic north but inclined slightly upward and perpendicular to the steeply inclined earth's field. Thus the ambient field is shallow in inclination but random in declination relative to the specimens' reference frames, since their bearing values are randomly distributed. Also, the earth's field is nearly perpendicular to the NRM directions since spot measurements showed that these are usually steep downward in the specimens' reference frames. This procedure minimizes any systematic effect of the earth's field on specimen NRM's. Prior to coring sample orientations in storage were random; therefore during the entire storage procedure ambient field effects if present would tend to produce a randomizing influence on directions of remanence.

Natural remanent magnetic moments of specimens were measured with a Schonstedt Model SSM-1 Spinner magnetometer, which is available commercially. For each measurement six spins were used with the specimen pointed in two opposite directions along each of three mutually perpendicular axes. To some extent this averages errors due to positioning of the specimen in the holder, and due to heterogeneity of the specimen.

An estimate of accuracy was made by selecting a specimen at random from the collection and measuring its NRM ten times repetitively each time removing the specimen from the Delrin holder. This was done in three or four carriage positions available, each producing a different distance between the specimen and the fluxgate sensor. A specimen appears less like a perfect dipole as it approaches the sensor, and thus a differing measurement is likely to result in different carriage positions.

The results are listed in Table 3-1. The mean of ten independent measurements (with the specimen entirely removed from the apparatus between measurements) is entered for each carriage position. An F-ratio test between the three pairs of measurements showed that in all cases they are distinct at a probability level greater than 99.9%. In each case excellent repeatability is obtained in each carriage position. The mean intensities are also significantly different but the source of errors is different for these, which depend on mechanical calibration of the carriage position stops.

The apparent discrepancy in direction between carriage positions is about one degree, which will be introduced as an error. The error within a carriage position, probably mostly due to inaccuracy of alignment of the specimen in the holder, is better than this, amounting to about half a degree (θ_{63}). The latter is random while the former is systematic and probably due to increasing deviation from an effective point magnetic dipole with approach to the sensor. Part of this is rock heterogenity introducing an error of an unknown amount in other specimens,

TABLE 3 - 1

Spinner Magnetometer: Repeatability of Measurement

Carriage Position:	Nearest	2nd Nearest	3rd Nearest
$\bar{D}$	143.9°	144.5°	143.3°
$\bar{I}$	51.7	53.0	54.1
Relative J	9.71	11.04	9.95
k	31000	66000	18000
R	9.9997	9.9999	9.9995
α_{95}	0.3	0.2	0.4
Standard Deviation in J [1]	0.03	0.02	0.54
θ_{63} = Standard Deviation[1] of directions	0.5	0.3	0.6
N	10	10	10

Definition of Variable Names:

D = declination, from true North, of direction of magnetization

I = inclination from horizontal of direction of magnetization (+ up, -down)

R = resultant of vector sum of individual directions taken as unit vectors

k = precision parameter = $\frac{N-1}{N-R}$

α_{95} = estimate of angular radius of cone containing the true mean vector with a probability of 95%

θ_{63} = angular radius of cone containing approximately 63% of the individual vectors

1 Standard deviation from the mean, of individual measurements

which must vary greatly between horizons, specimens, and samples. The only practical way of removing this is by use of statistical techniques to be applied to a number of specimen directions. In this specimen the non-dipole error can be estimated at approximately the between-carriage position error, or about one degree. Thus total angular error in measurement of NRM is nearly two degrees and this estimate can be extended to measurement of any magnetic remanence of reasonable stability. Inaccuracy in measurement of magnetic moment is about ten percent between carriage positions, and about one-quarter percent within the two nearest positions and five percent for the farthest position. The sources of this error are not known, but accuracy in measurement of magnetic moment is not as important as accuracy of direction.

Ease of measurement decreases with distance from the sensor since a longer time constant must be used, and especially with specimens of moderate to low intensity of remanence, as are mainly present in this collection. Here repeatability is best in the second closest position but only slightly less in the nearest position. Therefore all measurements were made in the nearest carriage position except in very rare cases where a remanence exceeded the capacity of the system and the second position was used. All specimens studied were easily measurable in this manner and thus variation of accuracy with M is not expected to be significant.

3.2 Directions of NRM

Fig. 3-1 and Table 3-2 show examples of specimen directions from six sites and Fig. 3-2 and Table 3-3 show site mean directions (taken

FIGURE 3-1: EXAMPLE DIRECTIONS OF NRM OF SPECIMENS

Wulff stereographic projection

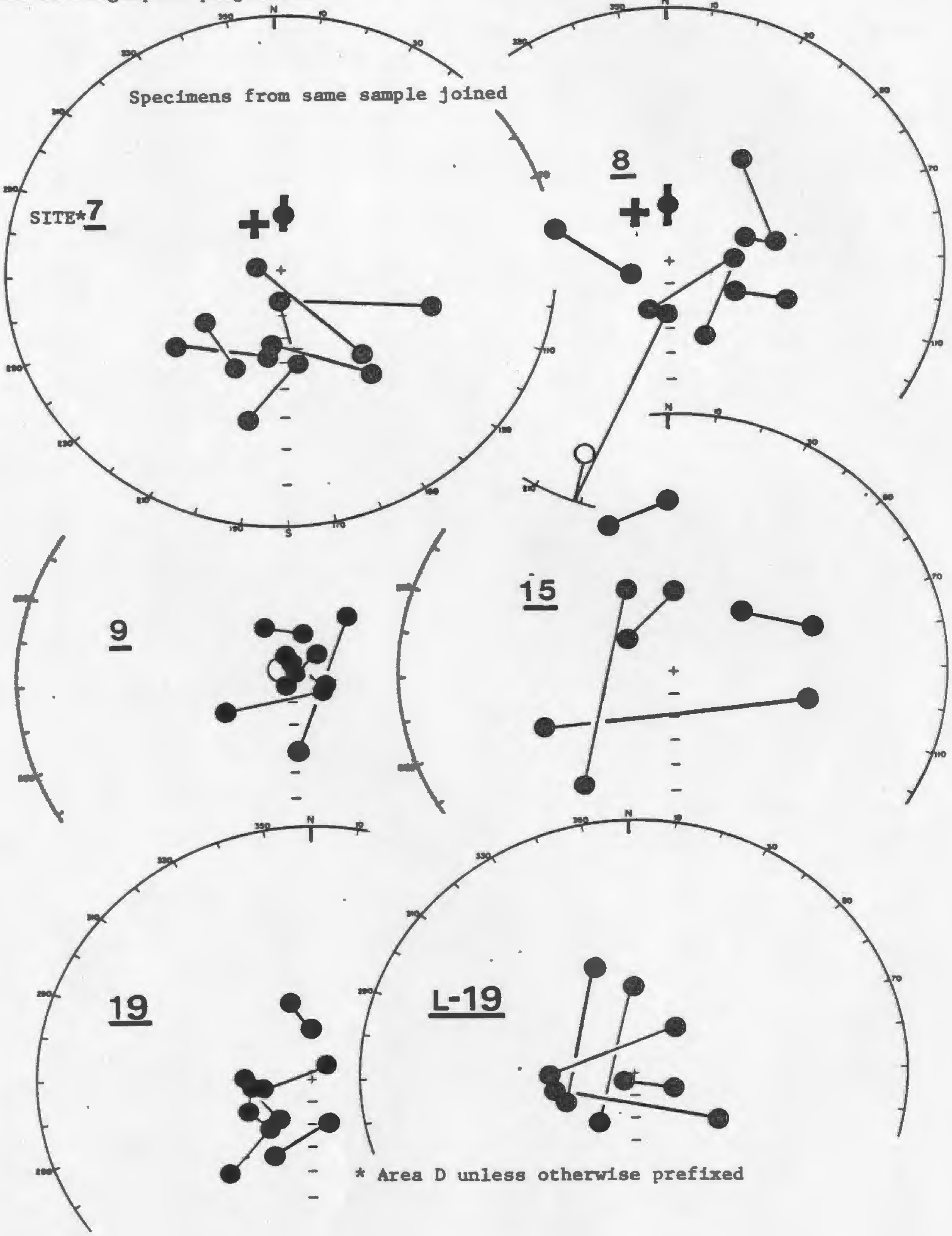


TABLE 3 - 2

Examples of Specimen NRM Directions and Sample Mean Directions of NRM

Sample	Specimen	D	I	Specimen	D	I	$\bar{D}$	$\bar{I}$	k[1]
Area D,		Horizon 7							
17	1A	171	+48	1B	192	+29	160	+52	8.5
	2A	180	+76	2B	106	+32			
43	A	205	+46	B	233	+51	218	+49	36
159	A	266	+81	B	137	+41	147	+68	5.4
169	A	183	+56	B	139	+34	156	+47	9.6
216	A	188	+52	B	231	+43	211	+49	15
Area D,		Horizon 8							
19	1A	160	+53	1B	71	+58	80	+59	6.7
	2A	81	+48	2B	36	+40			
44	A	184	+66	B	203	-11	197	+28	2.2
160	A	248	+72	B	286	+44	275	+59	12
170	A	202	+67	B	85	+64	138	+76	7.7
217	1	110	+44	2	118	+61	113	+53	42
Area D,		Horizon 9							
65	A	46	+86	B	42	+76	43	+81	131
66	A	213	+86	B	8	+81	350	+87	81
68	A	175	+60	B	43	+57	103	+76	4.1
69	A	97	+78	B	2	+84	69	+83	68
72	A	10	+70	B	338	+65	352	+68	77
73	A	243	+61	B	116	+75	211	+78	8.4
Area D,		Horizon 15							
37	A	245	+35	B	105	+39	179	+65	1.5
78	A	358	+58	B	305	+66	335	+64	21
79	A	331	+51	B	217	+32	261	+58	2.2
80	1	49	+53	2	72	+35	62	+45	22
81	A	358	+24	B	339	+27	349	+26	43
Area D,		Horizon 19							
5	1A	241	+60	1B	217	+46			
	2A	217	+62	2B	218	+39	227	+55	30
	3	258	+64						
112	A	56	+67	B	46	+55	50	+61	79
113	A	267	+63	B	216	+68	244	+68	30
114	A	204	+53	B	167	+69	190	+62	24
115	A	46	+83	B	257	+70	272	+83	19
Area L,		Horizon 19							
229	A	293	+52	B	40	+65	332	+69	5.3
230	1	210	+68	2	360	+52	327	+79	4.0
231	A	122	+52	B	256	+58	179	+74	3.3
232	A	341	+44	B	251	+61	307	+61	4.8
233	A	116	+74	B	226	_85	134	+82	39

1: precision parameter

between samples) of NRM. In general it appears that scatter in directions within a sample is of about the same order as scatter between samples and within a site. Notable in Table 3-2 is the large variation in k within each site, suggestive of within-site heterogeneity but partly due to small numbers of specimens within each sample. Correlation between within-sample precision and proximity of a sample mean to the site mean is sometimes present (for example, horizon 8) and sometimes absent (horizon 15). In the latter case distortions in the bedding may be the cause, but this is not likely to be a major effect if most of the magnetization is secondary, nor was it obvious in the field. In fact, in this example more distortion appeared to be present in the area of horizon 8.

The degree to which mean directions overlap the present earth's field (333°, + 20°) or dipole field (0°, +65°) at the sampling locality varies from site to site, and no correlation with within-site dispersion is apparent. In half of these examples the specimen directions are distributed distinctly southward of the present field, while in the other half some overlap appears.

Table 3-3 lists site means taken as the means between sample mean directions, before and after geological tilt correction. These are plotted in Fig. 3-2 before correction for tilt, on a Wulff stereographic projection.

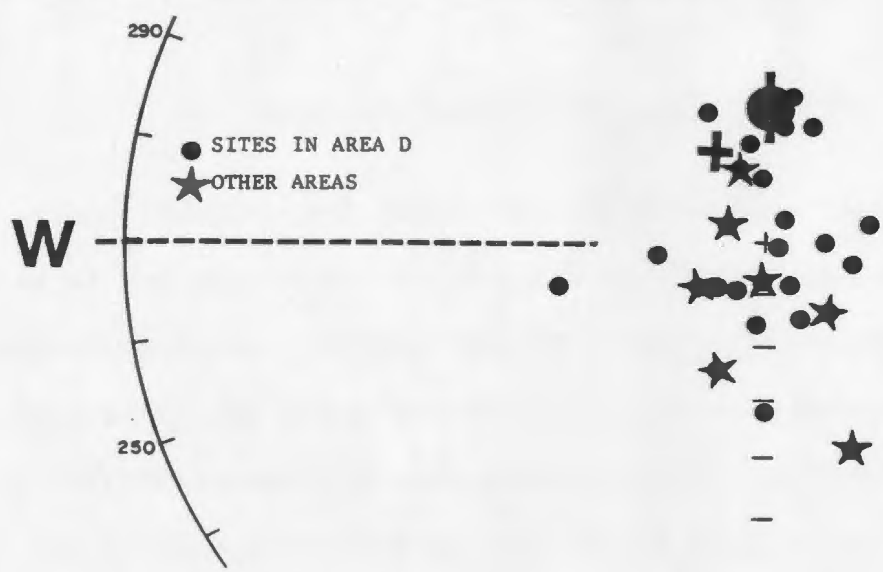
It is apparent from Table 3-3 and Fig. 3-2 that the error circles of most sites overlap, since they mostly exceed the angular separations between site mean directions. This feature is compatible with a single direction of magnetization being recorded in the rock unit. Directions taken from widely separated sites in the top red mudstone layer

TABLE 3 - 3
Site Mean Directions of NRM

Site		Direction of NRM		Corrected for Tilt		Within-Site Statistical Parameters				
Area	Horizon	D	I	D	I	N	n	R	k	α_{95}
D	1	335	+64	74	+63	5	18	4.626	1.8	55
	2	256	+53	178	+66	4	10	3.725	11	29
	3	356	+77	95	+53	5	12	4.902	41	12
	4	6	+65	75	+49	4	8	3.387	4.9	46
	5	126	+86	115	+45	5	22	4.618	10	25
	6	186	+73	135	+41	4	8	3.894	28	18
	7	181	+57	149	+29	5	12	4.733	15	20
	8	158	+73	128	+35	5	12	4.130	4.6	40
	9	39	+86	108	+41	6	12	5.876	40	11
	10	261	+70	123	+65	4	8	3.807	16	24
	11	158	+81	114	+43	5	12	4.571	9.3	26
	12	214	+78	116	+48	5	10	4.509	8.1	29
	13	94	+80	98	+34	3	6	2.903	21	28
	14	81	+72	103	+32	4	8	3.662	9.0	32
	15	348	+73	91	+56	5	10	3.972	3.9	45
	16	110	+75	111	+23	4	11	3.072	3.2	61
	17	6	+67	82	+43	3	8	2.636	5.5	59
	18	19	+68	84	+38	3	12	2.911	22	27
	19	221	+78	128	+43	5	13	4.589	9.7	26
G	18	226	+75	135	+52	6	12	5.259	6.7	29
	19	343	+74	85	+49	8	16	7.357	11	18
C	19	174	+82	145	+40	6	12	5.776	22	14
	20	143	+73	147	+30	4	8	3.409	5.1	45
L	17	195	+63	223	+49	5	10	4.318	5.9	34
	18	162	+50	198	+39	5	10	4.047	4.2	42
	19	294	+82	289	+42	5	10	5.776	22	16

N = number of samples   n = number of specimens; other symbols see table 3-1

FIGURE 3-2 : SITE MEAN DIRECTIONS OF NRM TAKEN BETWEEN SAMPLES



are not significantly dissimilar, although in two cases structural orientation diverges by an appreciable angle from that of the main sampling area.

Table 3-4 provides mean directions and statistical parameters taken between sites, both corrected and uncorrected for structural orientation. This is applied three different ways: to area D only, each horizon having unit weight; to all horizons in all areas with each site within the same apparent horizon (19) having a separate weight in each area, and to area D excluding the top horizon. Statistical precision, k, is not significantly changed by tilt correction of the site means within area D since bedding tilt is nearly uniform here, although slightly less precision is obtained after tilt correction. But k becomes less than half with tilt correction for the mean including all areas, implying a negative fold test for the natural remanent magnetization. This requires that the dominant component of NRM was acquired after folding of the beds.

3.3 Remanent and induced magnetization

Susceptibility and volume measurements were applied only to about one third of the specimens; those later to be involved in the pilot demagnetization study. Susceptibilities at room temperature were measured with a susceptibility bridge of the Christie and Symons (1969) type modified (for measurement of susceptibility vs. temperature) by Patzold (1972). An oscillating field of .031 mT is applied to the specimen, representing natural conditions, since the earth's field is roughly of this order, and this is low enough to avoid disturbing the NRM.

TABLE 3 - 4

Between-Site Mean Directions of NRM

	D	I	α_{95}	N	k	R
Area D only	110	47	8.7	19	16	17.868
	315	89	8.5	19	17	17.915
All Sites	120	52	11	26	7.3	22.592
	202	87	7.3	26	16	24.452
Area D without uppermost horizon	109	47	9.1	18	15	16.897
	340	88	8.9	18	16	16.937

Upper entry: Mean of site mean directions corrected for geological tilt

Lower entry: Mean of site mean directions uncorrected for geological tilt

Intensities of NRM (jn), susceptibilities (K), and Koenigsberger ratios ($Q_n = J_n/KH$ where H = 39.8 Am^{-1}, the approximate value of the present field) are listed in Table 3-5.

The Q_n ratio is a useful rough measure of stability of NRM since it represents the proportion of remanent magnetization (measured in zero magnetic field) to that induced in natural conditions. If a large part of the magnetic material carries only induced magnetization, this will produce noise during measurement, and instability during experiments. Thus Q_n increases with stability, and observations from other rock units provide a rough guide: Q_n values less than 0.1 are associated with the presence of significant unstable components while values greater than 1.0 are usually found in stable magnetizations (Irving, 1964). Most of the values here fall in neither range and may be compatible with either stable, unstable, or intermediate types of magnetization. Scatter in Q_n is not very great, and no systematic variation through the formation is apparent since the scatter within sites is as large as that between sites.

TABLE 3-5

NRM Values, Susceptibilities, and Koenigsberger Ratios of Pilot Specimens From Some Horizons

AREA D					HORIZON 19				
Horizon	Specimen No.	Jn (10^{-2} A/m^{+})	K (x100)	Q_n	Area	Specimen No.	Jn	K	Q_n
3	14-1A	1.5	2.8	.13	D	5-1A	3.7	.19	.48
	165A	4.8	.8	.15		112A	4.3	.28	.37
						112B	3.6	.25	.35
5	12-1A	11.8	1.1	.26		113A	4.9	.25	.48
	12-1B	11.7	.5	.52		115A	5.2	.72	.18
	15-2A	1.3	.2	.14					
	50-2A	1.9	.22	.21	G	116B	13.5	1.20	.28
	167-2A	1.8	.24	.19		117B	11.2	1.02	.27
						119B	5.2	.33	.39
7	17-2B	2.0	.23	.22		121A	3.1	.41	.19
	43A	1.4	.30	.11		124A	1.8	.33	.13
	43B	2.1	.26	.20		125A	7.9	.92	.21
	216B	3.7	.38	.24					
					L	229A	7.0	.65	.27
8	160A	.78	.12	.15		230-1	5.6	.57	.24
	170A	.10	.14	.01		231A	2.3	.18	.31
						231B	1.7	.22	.19
9	66B	.33	.04	.18		232B	3.0	.32	.23
	69B	.52	.05	.22		233A	6.6	.88	.18
12	32A	1.3	.11	.29					
	219-1	.98	.09	.25					
	221A	3.5	.45	.19					
15	78B	6.1	.93	.16					
	81B	8.4	.94	.22					

CHAPTER 4

PILOT DEMAGNETIZATION STUDY

4.1 Introduction

The basic method of finding the mean direction and stability of one or more components of magnetization in a rock unit is to demagnetize many specimens from the rock unit in a stepwise manner. Successively more stable portions of the natural remanent magnetization are removed by application of successively more intense demagnetizing treatment, or cleaning, at each step. The magnetic directions obtained by measurement of the individual specimens (with a Schonstedt station magnetometer) after each cleaning step are combined in a mean using Fisher's statistics (Fisher, 1953). A mean direction can be calculated only from specimens subjected to the same cleaning step, unless the magnetic constituents of the specimens are known to differ in some suitable manner.

A large number of vectors must be used in the mean found at each step in order to obtain sufficient statistical confidence. Also, the steps must be close together to avoid missing magnetic components with a narrow range of coercivity or blocking temperature. A prohibitive amount of time would be required to treat a large number of specimens each in great detail. Therefore demagnetization in a large number of steps is applied to a small number of specimens representative of the collection as a whole. This is the pilot study.

Fisher statistics may be applied to this preliminary data as an aid in deciding which treatment is optimal for the large number of remaining specimens. Other criteria may also be useful. A constant direction carried through several cleaning steps indicates a single stable magnetic component. A constant vector difference between directions obtained at consecutive cleaning steps in a certain demagnetizing range implies the presence of two components with one being preferentially removed. More complicated directional changes, which are usually difficult to interpret, indicate two or more components with two or more of these being simultaneously demagnetized, or inability of the rock to accurately record a paleo-field direction due to instability or heterogeneity. The pilot study is the initial experiment whose purpose is to decide optimum treatment for the bulk of the collection, and to determine the magnetic components present in the rock unit.

Both alternating field (AF) and thermal demagnetization methods were used to provide the greatest chance of obtaining stable magnetic components from rocks with different types of coercivity and blocking temperature distributions. For example, two magnetic components may reside in grains of similar coercivity but different blocking temperatures, or vice versa. The large coercivity of the very common magnetic mineral hematite is not within the range of most AF demagnetizers but its blocking temperature is easy to attain. On the other hand, better results may possibly be obtained by AF treatment than thermal, particularly if the magnetic minerals present are sensitive to oxidation during heating.

In the pilot study AF treatment was applied to 37 specimens and thermal treatment was applied to 36 specimens, all of these coming from 67 samples. Five samples were split with one specimen each for AF and one for thermal treatment, and AF treatment was applied to two specimens from one sample. The other 61 specimens were from 61 different samples. All sites whose NRM's were measured, except two, were included in the pilot study. The two sites excluded were the two lower horizons in area L, due to poor sampling characteristics, meaning lack of a well-defined bedding plane or irregularity of sample shape. The selection of specimens for the pilot study is shown in Table 4-1. Further details of the procedure are described in other sections of the chapter.

During demagnetization a major source of apparent error, which is sometimes of a misleading nature, is heterogeneity of the rock sample. A strongly magnetized pebble hidden in a specimen will produce a randomly directed magnetic component which may become demagnetized at lower alternating fields than the matrix. Apparent will be an additional component of magnetization which will not be reproduced in other specimens from the same site, or even those from the same sample. It is assumed that this effect acts randomly and is therefore mostly removed statistically.

For example, specimen 14-2A in Fig. 4-6 (pg. 84) may have a false component of this nature. The direction of remanence nearly follows a great-circle path on the stereographic net between 2½ and 40 mT, implying removal of a secondary component, dipping steeply downward to the east, overlying a harder primary component of unknown inclination having a westerly declination. Other specimens showing a similar great-circle demagnetization path often contained an apparent primary direction of an entirely different declination. Lack of reproducibility probably indicates that, in specimens like T-14-2A, a heterogeneous feature is producing a spurious component of magnetization more stable than the magnetization of the matrix.

TABLE 4 - 1

Selection and Treatment of specimens in pilot demagnetization study

Site	Specimen and Treatment			
Area D	Alternating Field		Thermal	
Horizon No.	Specimen No.	Highest Field*	Specimen No.	Batch No.
1	8-2A	L	9-1	5
	11-1B			
2	22-2A	180	164B	3
			212B	3
3	14-2A		14-1A	3
	165A			
4	158A	80	215B	5
5	12-1A	L	12-1B	1
	50-2A		15-2A	1
	167-2A			
6	168-1			
	168-2	L		
7	17-2B		43A	1
	43B		216B	1
8	160A	50	70A	4
9	66B	80	69B	4
			73B	5
10	56A	80	59B	4
	57A	70		
11	60A		29-1B	5
	61A			
12	219-1	80	32A	3
			221A	3

Site		Specimen and Treatment			
		Alternating Field		Thermal	
Area	Horizon No.	Specimen No.	Highest Field*	Specimen No.	Batch No.
D	13	222A	60	33-1	4
	14	84A	70	83B	4
	15	81B	60	78B	5
	16	102-2	250	103-2B	4
	17	107A		104-2B	4
	18	111-1B		106-2B	4
	19	112A		5-1A	1
		113A		112B	3
				115A	1
G	18	175B	250	208A	5
	19	116B	L	119B	5
		117B		124A	2
		121A	160L	125A	2
C	19	137A		136B	5
				139B	5
	20	142A		141A	2
				144B	2
L	19	229A	1	231B	5
		230-1		232A	2
		231A	140	233A	2

*If not otherwise stated, 300 mT. L: cleaned with low-field unit to 80mT, otherwise high-field unit

4.2 Pilot AF demagnetization study

4.2.1 Apparatus and procedure

During each demagnetization step a specimen is subjected to an alternating magnetic field of amplitude H which is increased smoothly for two minutes to a maximum value H-max, held constant for 15 seconds, then decreased in the same manner to zero. During a time that is short compared with a significant change in H the specimen is tumbled uniformly about three axes in order that grains with axes of easiest magnetization oriented in any direction are equally affected. As H decreases, directions of magnetization in grains of coercivity equivalent to H are blocked into random orientations. As a result the directions of magnetization of all grains of coercivity less than H max are randomized relative to each other, and only the magnetization harder than H-max remains for measurement.

Two AF demagnetization units are available at Memorial University: a low-field unit which can attain an H-max value of 80 mT (Pearce, 1965) and a high-field unit which can attain H-max = 300 mT (modified by the late Dr. G. Pullaiah from a design by Earth Physics Branch, Dept. of Energy Mines and Resources, Ottawa). Both units have a three-axis tumbling mechanism with the main rotation axis, perpendicular to a Hemlmholtz type demagnetizing coil in the low-field unit, and parallel to a solenoidal demagnetization coil in the high-field unit. In order to null the earth's field in the working region the low-field unit incorporates an orthogonal set of Helmholtz coils about 100 cm. in diameter centered on the tumbling mechanism providing a nearly spherical volume 10 cm in diameter where the field is uniform within 0.1%. The high-field unit has a set of Parry coils about twice the dimensions and similar in configuration to the low-field unit. In both cases each pair of field-cancelling coils is powered by a Power Designs Model 2005 precision power source operated in a constant-voltage mode.

4.2.2 Sources of Error

4.2.2.1 Accuracy of the procedure

Accuracy in setting the peak demagnetizing field H-max is limited by several factors for each of the AF cleaning units. In both cases there is an error in reading the ammeter indicating the energizing current, negligible for the low-field unit but 2 - 5% for the high-field unit above 10 mT. In both cases the ammeter sometimes oscillated slightly, producing an additional error of about the same magnitude. In the low-field unit the error in setting H-max is greater because a variable electrolytic resistance, more difficult to control than the motor-driven rheostat of the high-field unit, is used to adjust H. This error is only 2 - 4% for the high-field unit but 5 - 10% for the low-field unit; thus overall error is about 5 - 10% for both units.

Prior to every few hours' use the cancelling field is set, using a Schonstedt Heliflux Model SM-1 station magnetometer to measure the field components in the working area, and the current in each field-cancelling coil is adjusted to bring the field in the working space to zero. Accuracy here is quite high, about 10 nT, but the field usually drifts by about 100 nT between settings due to diurnal variation and coil temperature fluctuations. However, the effect of any small ambient field in the working space is practically removed by specimen tumbling.

All remeasurements of remanence were made as quickly as possible after demagnetization and the time a specimen was exposed to the earth's field between treatment and measurement was kept to a minimum. However, exposure lasting half a minute prior to measurement and a few seconds between spins during measurement was unavoidable. Therefore some spurious alignment of remanence is possible, but this would decay to some extent during a typical 30 sec. spin prior to taking a reading.

4.2.2.2 Repeatability of Measurement

In some instances treatment of a specimen was interrupted between steps and a second measurement of the remanence was made, immediately before resuming treatment. Between measurements some of these specimens were shielded and some were exposed to the earth's field. The demagnetizing field, period of storage, and measurements of remanence prior to and after storage are listed in Table 4 - 2.

The three shielded specimens showed an angular change in direction of about two or three degrees, about the same as inaccuracy of measurement. Unshielded specimens other than T230-1 showed changes approximately toward the ambient magnetic field, both in the NRM and after demagnetization (to 25 mT in the case of T219-1). This demonstrates that the magnetizations are reasonably stable but include a small unstable component.

For the highest demagnetizing field of 200 mT applied to T230-1 an angular change in direction of 112° in the general direction of the

TABLE 4 - 2

Repeatability of Measurement After Storage Before and During A.F. Demagnetization

Site Area	Site Horizon	Spec.	Last Peak Field	Time Between Measurements (days)	Direction[1] Of Earth's Field	First Measurement D	First Measurement I	First Measurement J (mA/m)	Second Measurement D	Second Measurement I	Second Measurement J (mA/m)
D	5	50-2A	NRM	100	N	52	+55	19.5	52	+38	17.0
	7	43B	80	85	Shielded	292	-57	6.86	288	-55	6.90
		17-2B	80	20	Shielded	179	+16	5.02	176	+15	5.37
	12	219-1	25	1	Down	167	+77	1.99	215	+84	2.13
	16	102-2	20	1	Shielded	55	+63	34.9	48	+62	35.5
L	19	229-A	NRM	1	W	270	+56	69.7	293	+52	70.7
		230-1	NRM	1	NE	217	+65	57.1	210	+68	56.7
		230-1	200	5	NE	224	-1	1.94	112	-1	5.61

1 Inclination zero if not otherwise specified

ambient field and an increase in the magnetic moment by a factor of three occur in five days. In the same specimen a repeat measurement of the NRM showed a much smaller rate of change of remanence. This implies that a remanence is induced more easily as more higher coercivity grains get randomized by earlier AF demagnetizations in higher fields.

4.2.2.3 Errors in results obtained from high-field unit

When about half the AF pilot study was completed it was noticed that some specimens treated with the 3-axis unit showed fairly random behavior above a certain peak field followed at higher peak fields by directions steep upward and downward at each step in a random sequence. In order to test whether the demagnetizer itself was inducing a remanence specimens were oriented in a systematic way relative to the inner member of the tumbler. Four different orientations were used: top of specimen toward (down) or away (up) from the innermost gear and the specimen's North mark toward (in) or away (out) from the gap through which specimens were inserted. No obvious ocrrelation of magnetic direction with azimuthal orientation was found, therefore for simplification the north mark was maintained inward and the up and down orientations only were recorded. Of the 37 specimens in the AF pilot study, orientations of 16 were unrecorded and random, 7 were oriented with differing sequences of orientation, and 12 were oriented in the same sequence, up in evenly ordered steps and down in odd steps.

Examples of demagnetizations affected by recorded orientations are specimens 66B and 219-1 in Fig. 4-1 (pg 54). The effect is first manifested as directions alternating from shallow in inclination to steeply downward, with the intensity of magnetization much less for the shallow direction than the downward direction. It appears as though a steadily increasing magnetic component, aligned in a constant direction relative to the inner tumbler member, is added to a stable portion of the magnetization which decreases from step to step.

For the 12 specimens with the same orientation sequence the correlation of the sense of the change in magnetic inclination with orientation is demonstrated in Table 4 - 3. The sequence of peak fields in the first column is the standard sequence used in the AF pilot study, except in a few cases where only a few of these steps were used to save time. The number of measurements declines as H-max increases because many demagnetizations were terminated after it was thought that the orientation effect had completely masked the stable component. The change in inclination refers to whether inclination decreased or increased, relative to the previous step. The percentage given is the proportion of the number of measurements in each step showing this change. The last column shows the proportion of cases where the magnetic direction was deflected in a constant direction relative to the inner member, that is, toward the inner gear. The average value should be near 50% here if the apparatus is not inducing a component of remanence. All values except three are higher than this, especially at higher fields where an increasing effect might be expected, since an increasing proportion of the natural remanence is removed and redirected by the apparatus.

It is concluded that a component of magnetization directed toward the inner gear of the tumbler aligned approximately along the

TABLE 4 - 3

Correlation of Magnetic Inclination With Specimens' Orientation Relative to Inner Tumbler Member

H-max (mT) (Peak Field)	Orientation	Number of Measurements	1	2	3
2½	Up	12	75	25	25
5	Down	12	67	33	67
10	Up	12	75	25	25
15	Down	12	75	25	75
20	Up	12	33	67	67
25	Down	12	92	8	92
30	Up	12	33	67	67
40	Down	12	58	42	58
50	Up	12	8	92	92
60	Down	11	100	0	100
70	Up	10	20	80	80
80	Down	7	71	29	71
100	Up	6	20	80	80
120	Down	6	67	33	67
140	Up	6	33	67	67
160	Down	6	50	50	50
180	Up	6	17	83	83
200	Down	5	100	0	100
250	Up	5	0	100	100
300	Down	3	67	33	67

1) % of Specimens showing increase in inclination

2) % of Specimens showing decrease in inclination

3) % increased with Up and Decreased with Down

innermost tumbling axis is imposed on the specimen during demagnetization. The cause is unknown but possibly related to slightly uneven tumbling which cannot be avoided in any tumbling mechanism with a finite number of axes.

4.2.2.4 Sources of error in high-field unit

Another factor besides slightly uneven tumbling must be present in order to produce the observed error. It is difficult to see how an external field would produce any effect when combined with this lack of uniformity, as a form of anhysteretic remanent magnetization, since any anomaly in the tumbling rate must occur equally in two opposite directions. This would suggest that the cause is magnetization in the inner member itself, but surface cleaning and replacement of brass screws by plastic ones had no effect.

A further brief series of tests was carried out with a single specimen, T60A, repeatedly demagnetized at 80 mT. The same dependence of magnetic inclination I on vertical orientation as that previously observed, was found. Intensity of magnetization varied slightly with no systematic difference between upward and downward orientations. Therefore, as suspected, the effect cannot be due to oppositely directed components of natural remanence with very narrow coercivity ranges. No correlation of magnetization with azimuthal orientation was found, as previously observed.

Tumbling speed was varied and the same correlation of I with orientation as that previously found was observed when the tumbling speed was either increased or decreased by about 15%. Therefore it appears that coincidence of specimen orientation with the instantaneous direction of the demagnetizing field during tumbling is not the source of error.

During routine demagnetizations no correlation of specimen orientations relative to the demagnetizing coil, just prior to removal from the tumbler, with direction of magnetization was found, for several specimens. During these tests, when Specimen T60A was placed in the coil without tumbling and no alternating field but with power turned on, the magnetization was not altered. Therefore no leaking DC current appears to be affecting the results.

4.2.2.5 Errors in results obtained from low-field unit

The same specimen was tested at 80 mT with the low-field demagnetizer after the tests on the high-field unit. The low-field unit was suspected of inducing errors because of results such as those shown by Specimens T116B and T229A in Fig. 4-1. Here the magnetization becomes slightly sporadic at 70 and 80 mT just before the specimen is switched to the high-field unit for continuation at 100 mT.

These examples illustrate that the low-field unit error occurred whether or not specimens were strongly affected by the high-field unit error.

The specimen was oriented four different ways inside the low-field tumbler, with both the azimuth and vertical orientation varied. No systematic correlation of magnetic direction with orientation was found, and directions were observed to change when the orientation was not changed, with no pattern appearing.

When the specimen was treated again on the high-field unit, similar results to those found previously were obtained. It appears that a random magnetic component is induced by the low-field unit at peak fields higher than about 50 mT.

4.2.2.6 Significance of apparatus-induced errors

From these tests and results it appears as though both demagnetization units induce an artificial component of magnetization in a specimen during demagnetization. However, this effect is small enough for most specimens below about 50 mT that the error can be neglected in this field range. Some specimens resist the effect entirely up to fields as high as 300 mT, as will be shown in the next section.

4.2.3 Specimen Results

In Figures 4-1 and 4-6 (pg. 84) are plotted the directions of magnetization and normalized intensities for ten examples of specimens treated in the AF pilot study. The five in Fig. 4-1 were subjected to further experiments (Isothermal Remanent Magnetization Test) described in Chapter 6. The five in Fig. 4-6 are from samples containing other specimens which were thermally studied.

Specimens T167-2A (Fig. 4-1) and T12-1A (Fig. 4-6), which were switched from the low-field to the high-field unit at 100 mT, show increasingly random directions between 40 and 80 mT combined with increases in intensity. It appears that spurious components of remanence are being induced by the low-field unit, an effect described above. Between 100 and 300 mT directions are very steep upward and downward while intensities are nearly constant, possibly implying a natural effect at first sight but established as an artificial effect in the following section.

FIGURE 4-1: DIRECTIONS AND NORMALIZED INTENSITIES OF REMANENCE OF SPECIMENS MEASURED BETWEEN A.F. DEMAGNETIZATION STEPS

Peak fields indicated adjacent to corresponding points.

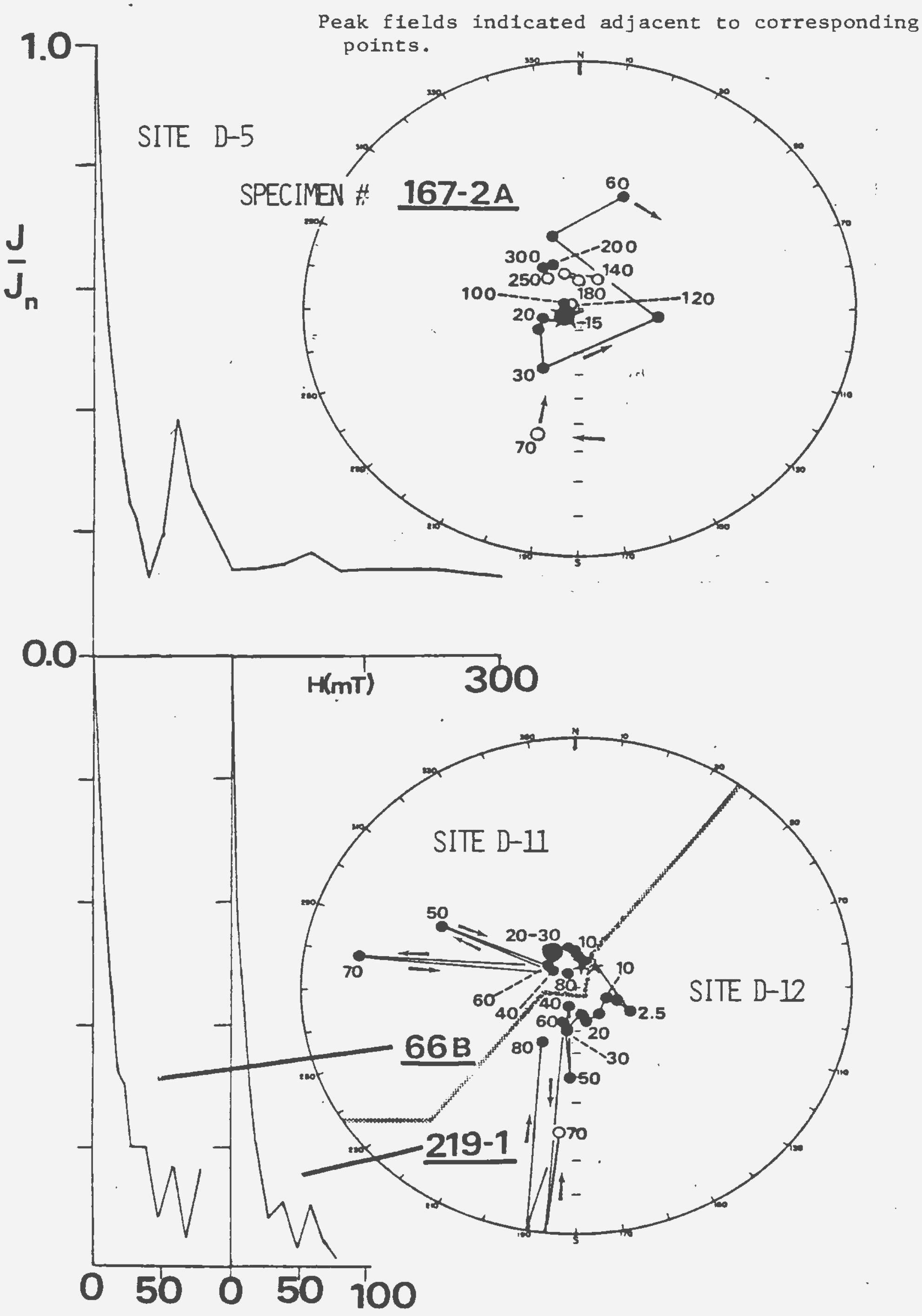
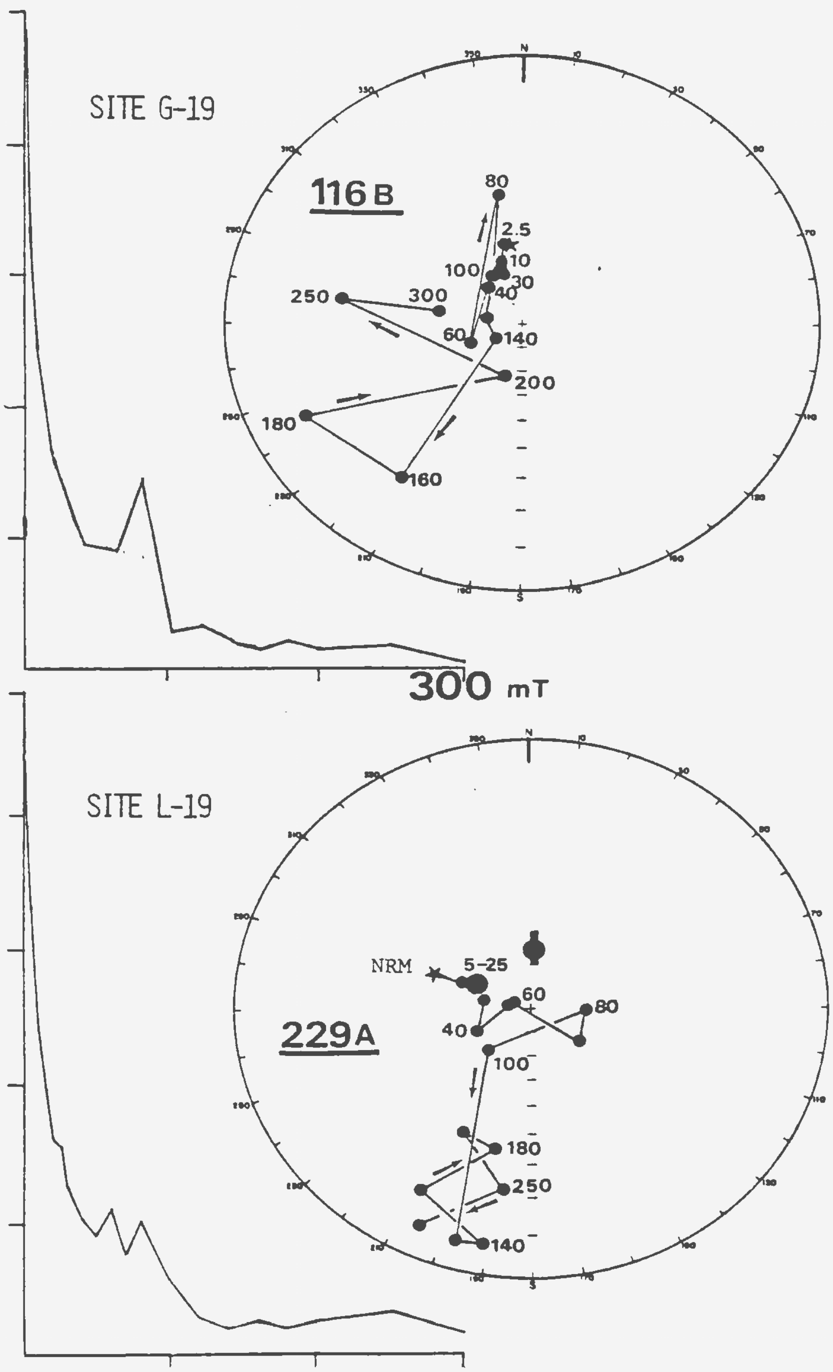


FIGURE 4-1 CONTINUED



foregoing sections.

Specimen T66B (Fig. 4-1) was treated with the high-field unit only to a peak field of 80 mT due to remagnetization, here occuring at a lower peak field than in most cases. Up to 40 mT the magnetization seems unaffected by the error and stable, changing only a few degrees in direction while declining by 80% in intensity. The NRM may be a single component of moderate stability directed steeply downward.

Specimen T219-1 (Fig. 4-1) shows a steeply downward-directed moderately stable magnetic component perhaps mixed with a smaller soft component producing minor scatter. At 40 mT the orientation effect begins to occur, up to this point probably not affecting the results, as in the previous example. In both examples magnetic intensity is greater with downward magnetization than upward; this difference is negligible below 200 mT, then increasing.

Specimen 116B (Fig. 4-1) showed instability when treated with the low-field unit at 60 and 80 mT but resumed a southward trend after being switched to the high-field unit. Above 140 mT, or possibly 160 mT, this trend is broken and instability appears, but no correlation is found with tumbler orientation, an observation that was repeated in a few other specimens but not in the majority of cases.

Specimens 229A and 231A (Fig. 4-6) are from the same site, the top horizon in area L, and illustrate the occurrence of different kinds of magnetic behaviour within the same horizon, which was often observed. Specimen 231A behaves almost the same as 167-2A (Hor. 5), showing instability at intermediate peak fields, then the orientation effect, Specimen 229A appears to contain two components of magnetization, one directed near the present earth's field, and another very stable component comprising only about 5% of the NRM directed southwestward and slightly downward in inclination.

It is possible that two other specimens, T14-2A (Fig. 4-6) and T116B (Fig. 4-1) contain a similar stable component, but in this and other similar cases scatter makes it difficult to obtain its direction with reasonable accuracy. About half the specimens in the top horizon showed this kind of southwesterly trend at high peak fields (and high temperatures) but scatter and completely different directions in other specimens made it difficult to see whether another component is really present. A small proportion of specimens from other horizons showed a trend toward the southwest at low peak fields but great circles fitting these trends would not intersect in a common small area due to scatter, probably caused by rock heterogeneity.

Specimens 14-2A, 43B, and 112A (Fig. 4-6) show stability or a great-circle movement above 2½ mT, but an NRM direction about 10° to 20° away from the first demagnetization step in a random direction. These specimens may possess a very soft magnetic component induced by a very recent natural or laboratory field.

The alternating-field demagnetization results can be summarized as follows:

(1) In nearly all specimens the apparatus-induced error is not significant below 50 mT and in some cases does not occur at all.

(2) Nearly all specimens show generally steep downward directions at low fields (50 mT), some not showing a significant change in direction at higher peak fields, and some showing a smooth change in direction

through a fairly small angle, as though two components of magnetization, differing slightly in direction, intensity and stability, are present. In these cases the apparently more stable components did not agree well in direction between specimens, and scatter was also present in the less stable component.

(3) Some specimens, mainly in the uppermost red mudstone layer, exhibited a very stable component comprising about ten percent of the total magnetization and directed nearly horizontally to the southwest. This was usually masked to a greater or lesser degree by an unstable component which caused the total remanence to change in direction by 10° or more between demagnetization steps.

(4) On average about half of the magnetization was lost at a peak field of about 10 mT.

4.3 Pilot thermal demagnetization study:

4.3.1 Apparatus and procedure

The thermal demagnetization unit is that described by Deutsch and Somayajulu (1970) with the addition of a field monitoring system in order that the earth's field and its variations in the working space can be cancelled automatically by feedback with an accuracy of about 1 part in 5,000 continuously.

Initial field cancelling is provided by a set of Parry coils similar to those in the high-field AF unit, powered by three constant-voltage precision power sources. A secondary set of coils of fewer turns wound over the primary set is powered by a triple feedback system controlled by three Schonstedt station magnetometers, each monitoring a field component at one of three points about ½ metre from the centre of the furnace and mutually separated by nearly one metre. The magnetic gradient between the working space and the monitoring points is compoensated by setting a neutralizing field in each of the station magnetometers. The vertical probe is used to set each primary coil with the secondary coils turned off. Neutralizing fields for the north-south and east-west magnetometers are set with their probes in the monitoring position. Then the vertical probe is quickly moved to its monitory position and its neutralizing field is set.

Temperature was measured with a thermocouple centrally located with respect to the specimens. If two shelves were used, temperatures above 500° C were corrected by addition or subtraction of 10° C depending on whether the specimens were placed on the top or bottom shelf respectively. This is the approximate value of the temperature difference at these temperatures, which was found to be about 12½°C at 700° C as discussed in Section 4.3.3. Lower temperatures were not corrected because consecutive steps are 100° C and above 500° C. With each heating five minutes were allowed for the specimens to reach thermal equilibrium at the peak temperature. Rates of heating and cooling were both about 10° C per minute.

During the pilot study six to ten specimens were placed in the furnace at one time and carried through all demagnetization steps in two to four days. Magnetic behaviour of specimens was observed during the study and temperature steps were adjusted depending on the temperature region at which the most interesting behaviour was expected to occur. Five runs (corresponding to batch # in Table 4-1) were made, the first three with 6 specimens each, the fourth eight specimens, and the fifth ten specimens. Up to 500° C temperature intervals were 100° C for the first, fourth, and fifth runs and 150° C for the second and third runs. The temperature sequence varied between specimens in a more complicated way above 500° C due to the correction for temperature gradient. Specimens were placed in the furnace in various orientations, which were recorded, and specimen positions and orientations were varied from step to step to prevent any small ambient field from producing a systematic effect. The furance was heated to a maxi-um temperature of 700° C in the first three runs and 650° C in the last two.

Remagnetization between treatment and measurement was minimized by leaving specimens in the working space after cooling until a few seconds prior to measurement, thus exposing them to the earth's field no more than during measurement.

4.3.2 Sources of error

4.3.2.1. Accuracy of the procedure

Accuracy in setting the primary currents and neutralizing fields is judged to be within 5 to 10 nT. This accuracy is retained for several days since monitoring accuracy is much better than this. Changes in the magnetic gradients, perhaps about the same as those in the earth's field, or one part in 100, will induce an error of about 1% of the vertical neutralizing field. Therefore the maximum field present in the working space during demagnetization is about 10 nT.

Accuracy of field cancelling was occasionally checked by turning the feedback system off, then setting the primary currents so that the magnetometers with neutralizing fields on read zero, with the probes in the monitoring positions. The field was then checked in the working space and found always to be less than 10 nT and usually less than 5 nT.

4.3.2.2 Magnetic gradients

Since specimens are spaced up to 8 cm apart horizontally and 4 cm apart vertically, magnetic gradients in the working space have some importance. Since these distances are only about one-twentieth of the Parry coils' separations, the gradients produced by these coils are assumed to be negligible and, at the most, less than the error in setting the cancelling currents and neutralizing fields.

Of more importance are fields due to nearby metallic equipment, which were minimized during installation. The Geomagnetic Research Laboratory itself is located away from any interfering man-made structures in a magnetically flat area. Since no magnetic objects exist within about 3 m of the working space it is unlikely that any appreciable magnetic gradients are present.

Partway through the pilot study it was found that cooling of the furnace could be enhanced by circulating air through the working area with a desk-top fan. The distance from the working space at which the magnetic gradient was unaffected by the fan's metal housing was found by rotating the fan 180° about each of three axes and roughly observing the field change in each case, measured with the magnetometer probes in their monitoring positions. These were a maximum of about 20 nT at a distance of 2 m and about half this at 4 m, with the fan in an easterly (magnetic) direction from the working space. The locally constant field produced in the working space by the fan is about 20 nT. With the fan at the 2 meter position the difference in field components at the sides of the furnace area closest and furthest from the fan, about 30 cm apart, were measured. These were nearly equal at about 15 nT, and were measured at about the same values with the fan in the 4 meter position.

The field difference across the 8 cm lateral specimen separation would thus be about 4 nT but was not measured due to the large dimensions of the wooden cube necessary for holding the fluxgate probe, and limitation of accuracy. Since the locally constant field of about 20 nT is mostly removed by the primary currents, the only error due to the fan is thus about 4 nT, increasing the total error in field nulling by perhaps about 50%.

4.3.2.3 Thermal gradients

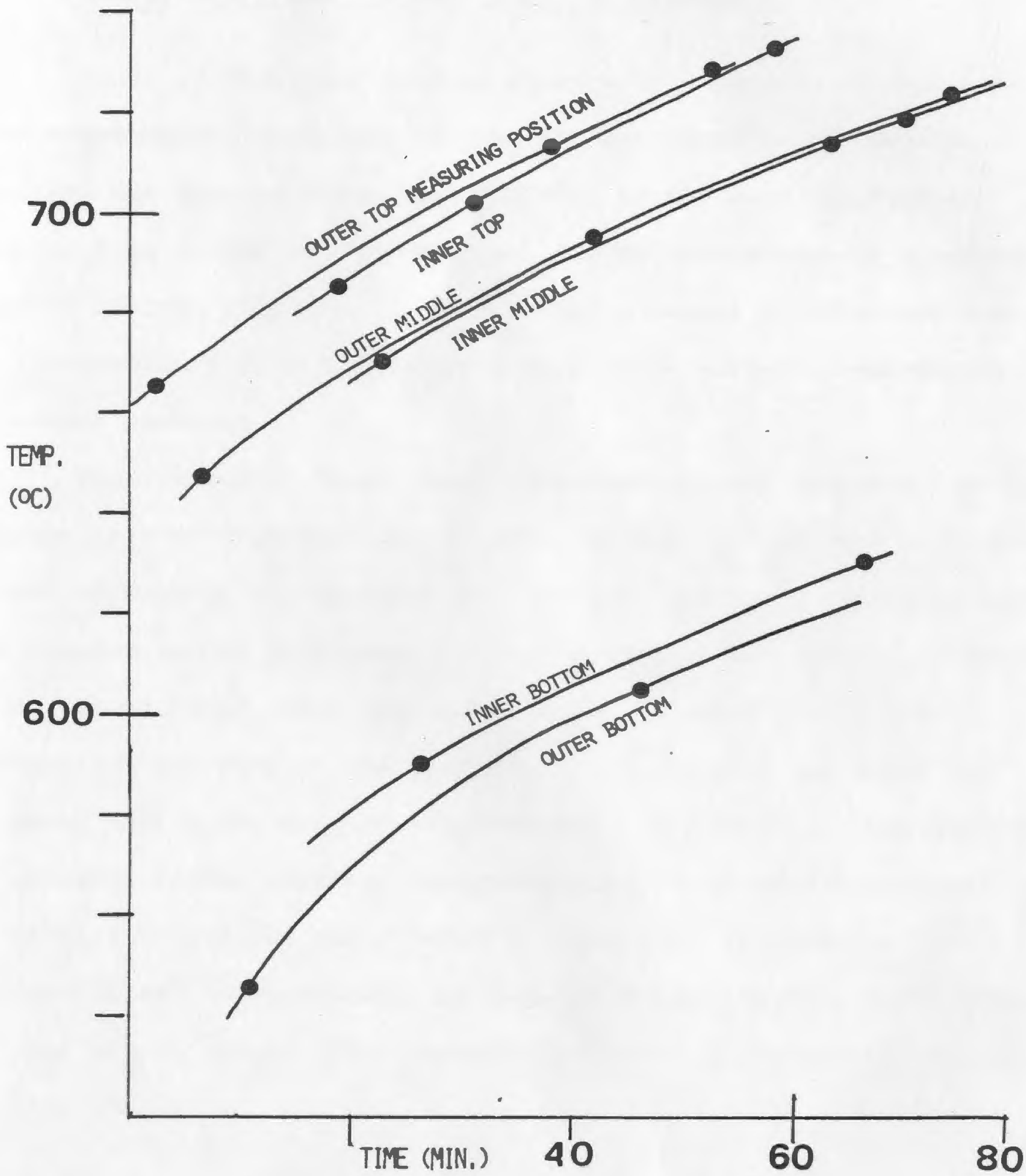
Thermal gradients in the working space were measured by allowing the furnace to approach thermal equilibrium at a certain temperature, then measuring the temperature at up to six places in the furnce with the same thermocouple as that used in the experiments. The measurements were made with the junction, enclosed in a ceramic housing, ½ specimen height, or about 1 cm, abvoe each of the three shelves which are 4 cm apart and 12 cm in diameter. The inner measurement was taken in the experimental measuring position, centered horizontally, and the outer measurement 4 cm outward at the same radial distance as specimens under treatment.

Measurements in all six positions, most of these taken twice, were made at 700° C with the perforated copper cap over the working area. This cap reduces thermal gradients and was used at steps of 400° C and higher during cleaning. Fig. 4-2 shows the results of these measurements plotted on a graph of temperature vs. time. In each position 3 minutes were allowed for the thermocouple to approach thermal equilibrium. Smooth parallel curves are drawn joining measurements at the same point in the furance. The vertical temperature differences are about 25° C between the top and middle shelves but nearly 100° C between the middle and lower shelves. Lateral gradients are negligible; about 3° C for the top two shelves, which were the only ones used during the experiments.

Thermal gradients were also measured at about 400° C with the cap on and off, at the central point of the middle and upper shelves, each measured twice. The difference was 19° C with the cap on and 45° with the cap off. Measurements involved in the latter calculation may be unreliable due to increasing temperature change in the furnace at the time this measurement was made.

It is evident that the temperature difference between the two upper shelves does not change very much between 400° C and 700° C, and that the perforated cap greatly reduces the thermal gradient. Measuring temperatures accurately is particularly important at higher temperatures where consecutive steps are closer together and where blocking temperatures are usually most highly concentrated. Total error in measurement of temperature is estimated at 5 to 10° C, about 2 to 3° C due to measurement of thermocouple temperature, and the rest

FIGURE 4-2 : MEASUREMENT OF THERMAL GRADIENT INSIDE WORKING SPACE OF THERMAL DEMAGNETIZATION UNIT



due to temperature differences between the specimens and the thermocouple.

4.3.2.4 Repeatability of treatment

Since in some runs heating steps were separated by about the same temperature difference as that between shelves, on occasion a specimen was heating twice consecutively to the same temperature (within five or ten Celsius degrees) due to interchange of specimens between shelves from step to step. This provides a convenient measure of repeatability at higher temperatures where suitable temperature intervals occurred.

The results of these repeat measurements are listed in Table 4-4. Extreme lack of repeatability is seen in samples from five horizons spread throughout the stratigraphic column in area D. Angular changes and changes in Jn, both upward and downward, are very large in every case. It is likely that heating above 580° C produces no useful information for much of the collection, and at best the upper limit is about 650° C for many of the horizons. The cause of this behaviour is probably either complete demagnetization at lower temperatures, due to heating beyond the Curie Point of magnetite, or chemical changes in the specimens. Repeatability at lower temperatures must be at least as good as the usualy small changes in direction observed at consecutive heating steps.

4.3.2.5 Errors in results

In the last thermal run specimens were maintained in a constant

TABLE 4 - 4

Repeatability of Measurement After Repeated Heating To Same Temperature

Horizon No.	Spec. No.	Temp (0°c)	First Heating D	First Heating I	First Heating J (mA/m)	Second Heating D	Second Heating I	Second Heating J (mA/m)
5	12-1B	650	200	+9	32.5	129	-47	16.3
7	216B	690	207	+12	2.95	350	-74	4.74
19	5-1A	670	54	+56	8.95	207	+36	2.36
18	106-2B	562	247	+76	.118	71	+56	.573
17	104-2B	587	303	-21	.941	91	-49	3.00

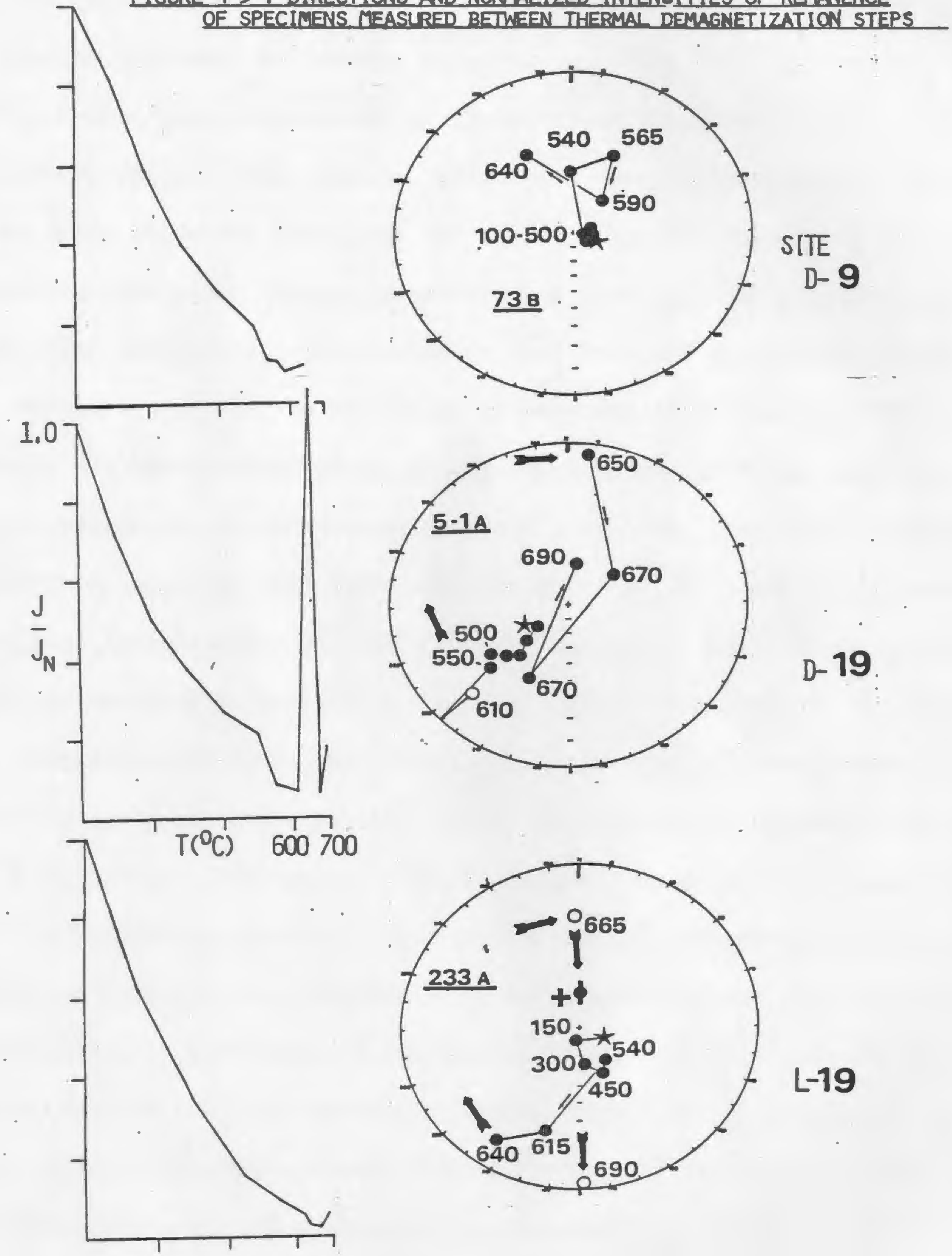
orientation throughout all heating steps to observe more easily than otherwise whether any systematic demagnetization effect is present. As usual half the specimens were oriented with their tops up and half with their tops down, adjacent specimens oriented oppositely. For high-temperature steps all 10 specimens revealed magnetizations in about the same direction relative to one another in their heating orientations. Those with their tops up were magnetized steeply upward and those with their tops down showed steep downward directions. Two examples are shown in Figures 4-3 (pg 69) and 4-6 (pg 84). Specimens 73B and 231B are stable in direction up to 500° C then appear to show another stable direction at high temperatures. These were oriented respectively with top down and N mark E, and top up and N mark W. Since the directions are nearly aligned when specimens are in their heating orientations, it appears as though remagnetization is occurring due to some ambient field in the furnace during cooling. However, after the run was completed a check of the field cancellation was made in the manner described above. The field in the working space was only 1 nT in the vertical direction and 2 nT in the north-south and east-west directions. This field is probably the cause of the apparent remagnetization, since a DC field in the heating coil cannot be the source, as the heating current is turned off completely during cooling. Another possible mechanism is specimen interaction, although this is not expected to be a dominant influence since specimens are placed with their centres a minimum distance of 4 cm apart. It appears that in most specimens no large magnetic components exist with blocking temperatures above 500° C or 550° C, and if present they are masked by unstable components.

4.3.3 Specimen results

Directions and normalized intensities of magnetization obtained after various cleaning steps for some specimens are shown in Figures 4-3 and 4-6. For nearly all specimens intensity showed a linear, or mildly exponential decay curve to about 500° C, sometimes followed by an abrupt increase in intensity. The same broad pattern in directions apparent in the AF pilot study is also seen in the thermal pilot study. Most specimens displayed a fairly stable direction close to that of the untreated NRM up to a temperature of 450° C to 550° C. The top horizon, which probably contains hematite, did not show a systematic retention of stability to higher tempeartures than those found in the lower horizons. The effects of cleaning varied so much, even within horizons, that no clear differences can be seen between horizons.

Some specimens, such as 14-1A (Fig. 4-6), 5-1A (Fig. 4-3) and 233A (Fig. 4-3), show a more-or-less well-defined tendency toward the southwest at higher temperatures. Trends toward shallow inclinations occur in other declinations, but most specimens showing this kind of behaviour display a tendency to the southwest. However, the majority of specimens show no trend at all, but seem to have a single component of magnetization caused by heating and at high temperatures masked by some randomly directed component. The top horizon in area L included two specimens with a clear southwest trend (T233A in Fig. 4-3) and one without a clear trend (T231B in Fig. 4-6). This southwest tendency was less prevalent in the top horizon in other areas and in the lower horizons, in both AF and thermal cleaning.

FIGURE 4-3 : DIRECTIONS AND NORMALIZED INTENSITIES OF REMANENCE OF SPECIMENS MEASURED BETWEEN THERMAL DEMAGNETIZATION STEPS



4.4 Statistical analysis of pilot study results

The purpose of this analysis is to find the type of treatment which yields the most favorable results in order that optimum use can be made of remaining specimens in the collection. The mean directions of specimens within each sample, site, and the formation as a whole are taken at each cleaning step and the most favorable treatment is judged by observing the statistical parameters K and α_{95}. The large number of remaining specimens are treated in one step of demagnetization.

During the pilot study it is often most efficient in the laboratory to demagnetize some specimens with fewer steps or with a different sequence of steps than others. In some cases it may be known from previous results that information will not be lost by increasing the interval between steps. In thermal demagnetization some specimens were heated to higher temperatures than others in hopes of finding a primary component of magnetization, and sequences of steps differed from specimen to specimen because of the thermal gradient correction.

A principle that must be followed in comparing the results of different cleaning steps is to use means calculated with an identical population of specimens. Otherwise a specimen present in one result and not another may produce an apparent change in mean direction or precision not due to real magnetic properties. For this reason a computer program was developed (see Appendix) to perform statistical calculations with all available data, then repeat each calculation, comparing it with other steps by eliminating specimens present in the original calculation but not present in the other steps. This computer program was used for performing most statistical calculations whose results are described in this chapter (but not chapters 3 and 5).

In all calculations of between-site means the top horizon has unit weight as a site in each separate area. Initial calculations were made without the bedding tilt correction since most demagnetized directions are similar to those of the natural remanent magnetization, which yielded a negative fold test.

4.4.1 Statistical analysis of AF pilot study:

4.4.1.1 Between-site means

In Tables 4-5 and 4-6 the between-site means are summarized, with specimens that were oriented randomly in the tumbler in an unknown sequence, and those that were oriented the same way for the same steps being calculated separately.

Table 4-5 shows means for all 20 AF demagnetization steps for those specimens whose tumbler orientations were unrecorded and random. In this case all specimens were demagnetized with the same steps up to 300 mT. Horizon 14 had been demagnetized at 20 mT intervals and was not entered in these calculations, since recalculation would then be necessary at these steps. This horizon revealed an almost vertical downward magnetization during the first part of AF cleaning but was very susceptible to the orientation effect, including the specimen T60A used in testing this effect.

The calculation was repeated for area D only in order to observe whether the outlying areas showed peculiar results, up to 60 mT only. Results are very similar in these two cases, and it appears that

TABLE 4-5 **Between-site Means After AF Cleaning For Specimens Oriented Randomly Relative To Inner Tumbler Member**

Sites Included: Area D Horizons 1, 3, 5, 6, 7, 19;
Area C Horizon 20; Area L Horizon 19

Peak Field (mT)	(1) Means Including All Sites; N=8 16 Specimens D	I	R	k	α_{95}	(b) Mean of Sites in Area D Only; N=6 13 Specimens D	I	R	k	α_{95}
NRM	173	+85	7.108	7.8	21	48	+87	5.573	12	20
2½	235	+87	7.121	8.0	21	340	+84	5.618	13	19
5	234	+85	7.127	8.0	21	319	+84	5.627	13	19
10	248	+81	6.952	6.7	23	294	+80	5.475	9.5	23
15	241	+79	6.933	6.6	23	281	+79	5.446	9.0	24
20	239	+78	6.781	5.7	25	271	+77	5.303	7.2	27
25	166	+85	6.737	5.5	26	55	+87	5.256	6.7	28
30	188	+85	6.075	3.6	34	358	+86	4.602	3.6	41
40	215	+78	7.063	7.5	22	253	+82	5.522	10.4	22
50	347	+71	5.481	2.8	41	353	+54	4.640	3.7	41
- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
60	130	+79	4.272	1.9	58	30	+76	2.827	1.6	85
70	205	+62	2.792	1.3	90					
80	216	+59	3.043	1.4	82					
100	211	+27	3.174	1.4	79					
120	236	+69	1.526	1.1	cos 1					
140	154	+52	3.231	1.5	78					
160	257	+ 4	3.551	1.6	71					
180	272	-23	3.100	1.4	81					
200	162	-71	.505	.9	cos 1					
250	252	-18	3.884	1.7	64					
300	230	+31	1.881	1.1	137					

All results below dashed line "random" (have precision less than that which could be produced by random grouping with probability of 5%)

TABLE 4-6 — Between-site Means After AF Cleaning For Specimens With Same Tumbler Orientations At Every Step

Sites Included: Area D Horizons 2, 4, 8, 10, 12, 14, 16, 17, 18; Area G Horizon 18; Area C Horizon 19. One Specimen per site

Peak Field (mT)	Orientation of Specimens In Tumbler	Means for all specimens cleaned at 100 mT. Sites D 2, 16, 17, 18; C18; C19. N = 6					Means for all specimens cleaned at 300 mT. Sites D17, 18; C19. N = 3				
		D	I	R	k	α_{95}	D	I	R	k	α_{95}
NRM	Up	4	+71	5.078	5.4	32	349	+66	2.586	4.8	64
2½	Up	357	+72	5.351	7.7	26					
5	Down	358	+73	5.441	8.9	24					
10	Up	355	+76	5.497	9.9	22					
15	Down	350	+78	5.519	10	22					
20	Up	344	+78	5.532	11	21					
25	Down	336	+78	5.604	13	20					
30	Up	338	+80	5.551	11	21					
40	Down	341	+80	5.615	13	19					
50	Up	332	+75	5.630	13	19	292	+76	2.726	7.3	49
60	Down	336	+82	5.701	17	17					
70	Up	326	+72	5.540	11	21					
80	Down	299	+79	5.645	14	18					
100	Up	349	+80	5.141	5.8	30	238	+79	2.387	3.3	84
120	Down	37	+85	5.313	7.3	27					
140	Up	312	+72	5.076	5.4	32	284	+72	2.288	2.8	95
160	Down	256	+73	3.325	1.9	70					
180	Up	250	+36	3.243	1.8	72	223	+64	1.799	1.7	cos 1
200	Down						256	+76	2.462	3.7	76
250	Up	All results below dashed lines					252	+39	1.582	1.4)	cos 1
300	Down	"random"					291	+66	1.063	1.0)	

directions found above 40 or 50 mT are statistically meaningless. Directions are very steep downward and do not vary significantly up to the point where k becomes small. Results marked "random" could have been produced by a random distribution of directions with a greater than 5% probability.

The precision parameter k shows a shallow maximum at 5 mT followed by a sharp peak at 40 mT. The first is compatible with removal of soft components in random directions followed by decreasing precision due to increasing magnetic "noise", which is caused by remagnetization of very soft demagnetized portions of the original NRM, and increasing noise in the magnetometer relative to the decreasing moment in the weakest specimens. This problem is common to all specimen demagnetizations, both AF and thermal, and places a lower limit on the proportion of the original NRM which is measureable. The origin of the peak in k at 40 mT is unclear but, since N is small, this feature could be fortuitous. Directions of individual specimens are listed in the computer printout in the Appendix.

In Table 4-6 are listed means taken between sites for specimens relatively oriented the same way at each step. In this case different specimens were demagnetized in slightly different sequences. Groups of specimens with the same sequence in common are labelled according to the step at which they first appear exclusively. In this case two groups are tabulated; those labelled 100 mT and 300 mT, including 6 sites and 3 sites respectively. The former is not carried in its entirety to 300 mT, therefore the latter group is included, with most steps at lower fields omitted for brevity.

It would be expected in view of the effect illustrated in Table 4-2 and described in section 4.2.2 that steps with "Up" orientations would show greater precision than steps with "Down" orientations. However, this is not the case, probably because different specimens exhibit the effect in different field ranges, and some not at all.

4.4.1.2 Precision of within-site means

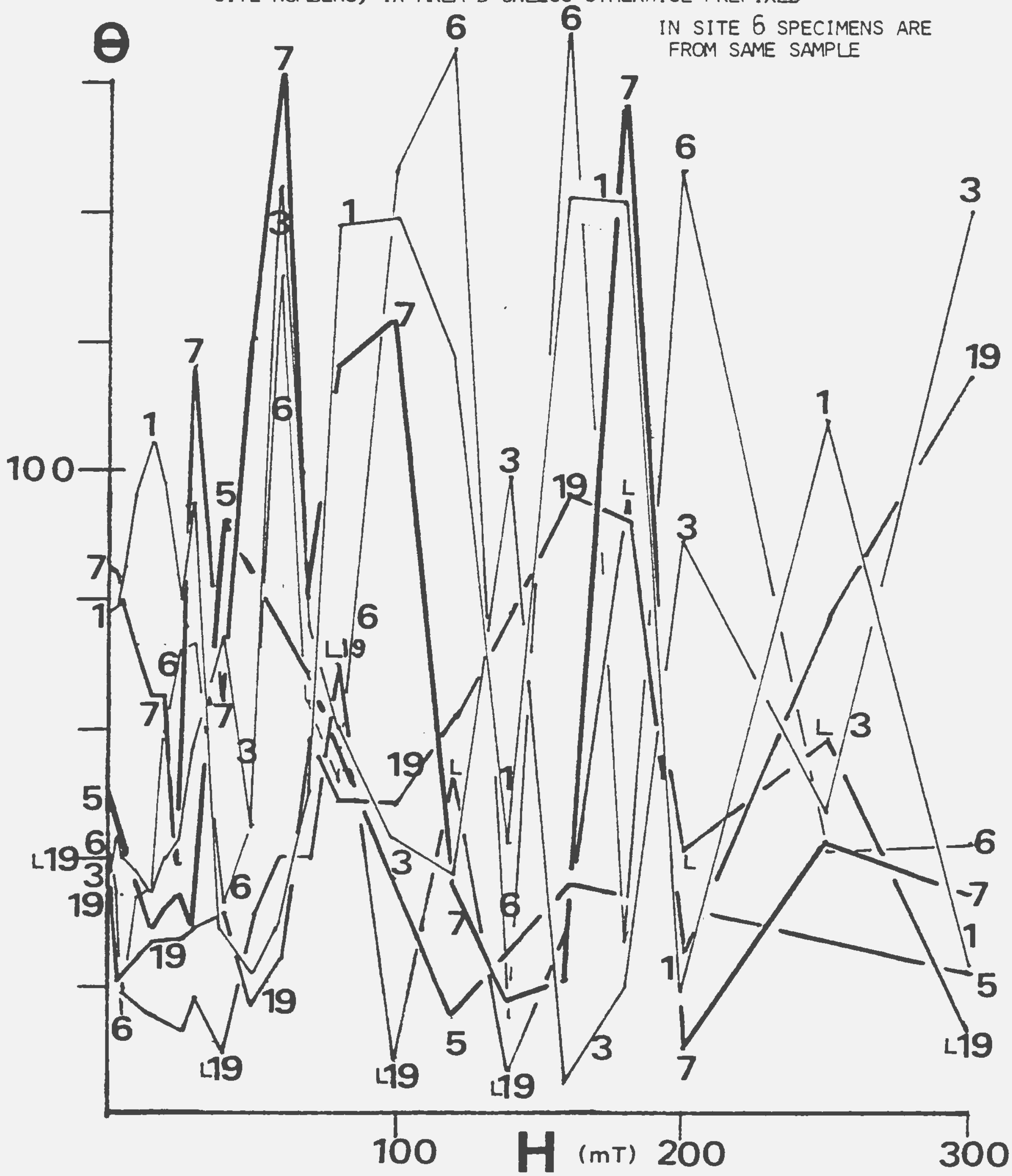
In order to check whether individual sites show uniform magnetic behaviour, angular separations (θ) of two specimens' directions within each site are plotted in Fig. 4-4. In the case of Horizon 6, two specimens come from the same sample; the only sample from which two specimens received the same kind of pilot study treatment. Only sites with specimens not systematically oriented in the tumbler are included here, in order that the orientation effect will be less systematic than otherwise. Thus, only broad trends in θ are significant, since isolated minima in these may be due to all specimens in a set by chance having the same orientation.

There appear to be smooth minima at 50 mT in Horizon 1 and at 40 mT in Horizon 19 in area L, but large fluctuations in θ are also present at lower and higher fields. Minimum values are less clear in the other horizons but precision is generally greater below 40 mT than above in the lower horizons. In the top horizon in area D high precision is apparently carried to higher fields than in the lower horizons.

FIGURE 4-4: CLOSENESS OF GROUPING OF DIRECTIONS OF REMANENCE OF SPECIMENS WITHIN SITES DURING A.F. CLEANING

SITE NUMBERS, IN AREA D UNLESS OTHERWISE PREFIXED

IN SITE 6 SPECIMENS ARE FROM SAME SAMPLE



4.4.1.3 Within-sample means

In Horizon 6 the angular separation is least at 5 and 40 mT, in accordance with the between-site calculation (Fig. 4-4). It is not known whether this effect is real, since it could be due to orientation.

4.4.2 Statistical analysis of thermal pilot study

4.4.2.1 Between-site means

Calculations were done for three different groups of sites: (a) all horizons in all areas (with the top horizon having unit weight in each area, (b) all horizons in area D, and (c) the top horizon in all areas (with each sample having unit weight). The top horizon was not calculated separately in the AF cleaning calculations because samples are too few after separation into oriented and unoriented groups.

In Table 4-7 (a) specimens are divided into three groups each demagnetized at several temperature steps (labelled by the starting interval) with exactly the same population of specimens. The first group includes all specimens in the thermal pilot study. At all other steps besides the NRM and 300° C some specimens were excluded, allowing comparison only between these two steps. For this group also k is about the same at 300° and at the NRM; in the others k shows a smooth increase followed by a smooth decrease. In the second group k is virtually the same at 100° C or 200° C, and in the third about the same at 150° C or 300° C. Thus the step at which optimum statistical precision is obtained is bracketed between 150° C and 200° C. Directions are consistently very steep downward and statistically different from the present earth's

TABLE 4-7 Pilot Thermal Demagnetization Study: Between-site Means

Initial Step Size, Peak Temp.	(a) All Areas D	I	R	k	α_{95}	(b) Area D Only D	I	R	k	α_{95}	(c) Top Horixon in All Areas D	I	R	k	α_{95}
(1) 300°C		N=24*	n=36*				N=18	n=25					n=13		
NRM	150	+88	20.355	6.3	13	58	+87	15.018	5.7	16	267	+80	12.172	14	11
300	202	+76	20.907	7.4	12	211	+78	15.384	6.5	15	207	+76	11.178	6.6	17
(2) 100°C		N=19	n=24				N=15	n=19					n=6		
NRM	121	+87	15.744	5.5	16	78	+85	12.445	5.5	18	273	74	5.765	21	15
100	233	+87	16.773	8.1	13	264	+87	13.240	7.9	14	247	80	5.713	17	16
200	190	+83	16.761	8.0	13	178	+86	13.224	7.9	14	222	76	5.472	9.5	23
300	202	+78	15.979	6.0	15	206	+81	12.542	5.7	18	209	72	5.231	6.5	28
400	205	+78	16.319	6.7	14	205	+80	12.971	6.9	16	223	71	4.923	4.6	35
500	234	+79	15.445	5.1	17	249	+81	12.272	5.1	19	234	73	4.708	3.9	39
(3) 150°C		N=8	n=12				N=4	n=6					n=7		
NRM	269	+83	7.351	11	18	310	+77	3.508	6.1	41	253	84	6.461	11	19
150	208	+81	7.541	15	15	209	+76	3/763	13	27	329	86	6.302	8.6	22
300	208	+71	7.519	14	15	220	+67	3.776	13	26	203	80	5.976	5.9	27
450	220	+71	7.144	8.2	21	233	+68	3.555	6.7	38	224	80	5.476	3.9	35
545						226	+46	3.333	4.5	49					
608						4	-39	1.404	1.2	-					
633	297	+47	4.676	2.1	52	304	+30	1.980	1.5	138	312	42	4.150	2.1	56
655						197	+63	1.494	1.2	-					
670						131	-9	1.338	1.1	-					

(1) All sites except Area D Horizon 6; Area C Horizon 20 divided intwo.
(2) Same as (1) without Area D Horizons 2, 3, 20 and Area C Horizons 20,21.
(3) Area D Horizons 2, 3, 12, 19, Area G Horizon 19, Area C Horizon 20, Area L Horizon 19,
*N = # sites, n = # samples, one specimen per sample. Mean calculated using N sample means in (a) and (b); using n specimen directions in (c)

TABLE 4-8

Thermal Demagnetization Results from Area L

Initial Step Size, Peak Temp.	Before Tilt Correction D	Before Tilt Correction I	After Tilt* Correction D	After Tilt* Correction I	R	k	α_{95}
(1) 300°C	N=3	n=5					
NRM	241	+73	272	37	2.810	10.5	40°
300	178	+78	269	53	2.377	3.2	85
608	139	+35	176	63	.880	.9	cos $_{95}$ 1
(2) 150°C	N=2	n=3					
20	218	+79	273	45	1.868	-	42°
150	31	+77	309	51	1.846	-	45
300	69	+76	306	60	1.687	-	65
450	76	+70	313	65	1.615	-	72
545	74	+72	311	63	1.754	-	57
633	236	+36	248	8	1.590	-	75
670	297	+8	299	-32	.851	-	130
689	204	+11	210	5	1.765	-	56

(1) Horizon 19 samples 231 (two specimens, 232 (two specimens) 233 (one specimen)

(2) Horizon 19 samples 232 (two specimens), 233 (one specimen)

* area strike = 198° area dip = 40° (to the west)

angular separation between the two sample directions field at D = 333°, I = +69°.

Exactly the same description applies to the results obtained from area D alone (Table 4-7 (b)), but k drops very slightly with removal of outlying areas. The third group of specimens from 4 sites is carried to a high temperature in many steps, showing that dispersion in this temperature region is very large.

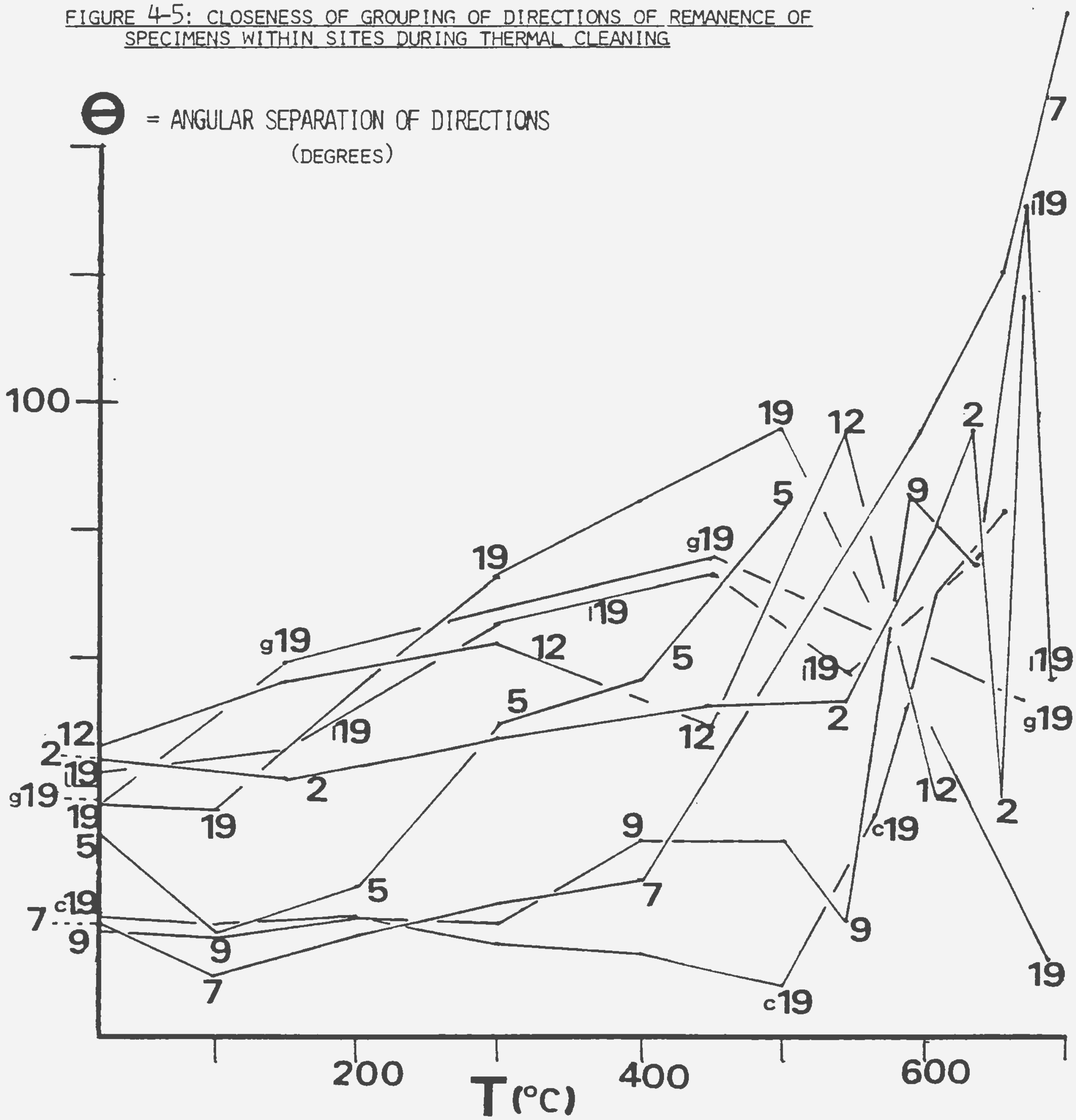
The top horizon (Table 4-7 (c)) was also divided into three groups for calculation and shows a direction slightly but not significantly west of area D, with greater precision. A major difference in the results here is that k declines steadily from the NRM value, indicating that thermal cleaning does not provide increased precision in the vector grouping. This may indicate that strong unstable components are present in the NRM and are being partly aligned in some random direction before or during measurement.

Since area L is the only westerly dipping area, data from it is listed separately in Table 4-8 with and without correction for bedding tilt. Some of these data are compared to those from the other areas by means of a fold test (Graham, 1949) described in Section 4.6.

4.4.2.2 Precision of within-site means

Angular separations (0) between two specimens each from different samples within a site are plotted in Figure 4-5. In sites with 3 specimens, some heating steps were applied to only two of these which are compared for steps at which they both were treated. The same pair cannot be averaged at higher temperatures if they were placed on different shelves, due to the gradient correction.

FIGURE 4-5: CLOSENESS OF GROUPING OF DIRECTIONS OF REMANENCE OF SPECIMENS WITHIN SITES DURING THERMAL CLEANING



The first step of demagnetization at 100° C or 150° C yields the smallest angular separations at low temperatures in most cases here. The minimum separation is present in the NRM's in sites D12, G-19, and L-19, but this is not a strong minimum and in each individual case is partly due to chance. However, in the other sites in the top horizon the first step of demagnetization does not yield a significant reduction in θ. Therefore results do not differ strongly from one area to another in the top horizon, and the true within-site optimum occurs at the same cleaning step as that found in the calculation for the top horizon as a whole, as discussed previously. For most of area D also, the best means are obtained almost at the same demagnetizing temperature as that revealed by the between-site calculation, but the third demagnetization step shows a comparatively greater dispersion.

4.5 Comparison of AF and thermal cleaning results

4.5.1 Between-site means

Comparisons of the results of AF with thermal treatment can be made for all horizons in all areas calculated together, and for area D only. For all areas Tables 4-5 (a) and 4-7 (a) may be referred to, although exactly the same group of horizons cannot be compared, mainly because the AF results were calculated separately for oriented (Table 4-6) and unoriented specimens.

Among the first few steps the values of k obtained are comparable except that k is higher in the thermal group with N = 8, which is a minority of the sites. Directions are not significantly different at the 95% confidence level and in both cases are almost straight downward and slightly to the south.

For Area D (Tables 4-5 (b), 4-7 (b)) by itself k is slightly better for AF cleaning than thermal and directions are slightly more northerly with AF treatment, but do not significantly differ from thermal treatment. The significance of this difference is partly reduced by the fact that only six sites are included in the AF calculation.

4.5.2 Comparison of within-site means

General trends can be compared directly for Horizons 5 and 7 or less directly by comparing different horizons such as 1 (AF) with 2 (Thermal) or 3 (AF) with 5 (Thermal), in Figs. 4-4 and 4-5.

In this manner it can be seen that, in the lower horizons (20 or lower) thermal treatment gives smaller angular separations between samples in the first few steps. AF treatment yields smaller angular separations in the top horizon in areas D and L. For the top horizon in area L little information is available while that in area C shows very small angular separation in thermal treatment, but no AF data is available.

4.5.3 Within-sample comparison

A very strong comparison of the two treatment methods can be made by applying both methods to the same sample, as was done in five cases. These demagnetizations are plotted in Fig. 4-6.

In every case the directions of magnetization converge fairly well at intermediate fields and temperatures. The poorest convergence

FIGURE 4-6 : COMPARISON OF DIRECTIONS AND NORMALIZED INTENSITIES OF REMANENCE OF SPECIMENS OF SPECIMENS WITHIN A SAMPLE SUBJECTED SEPARATELY TO A.F. AND THERMAL DEMAGNETIZATION

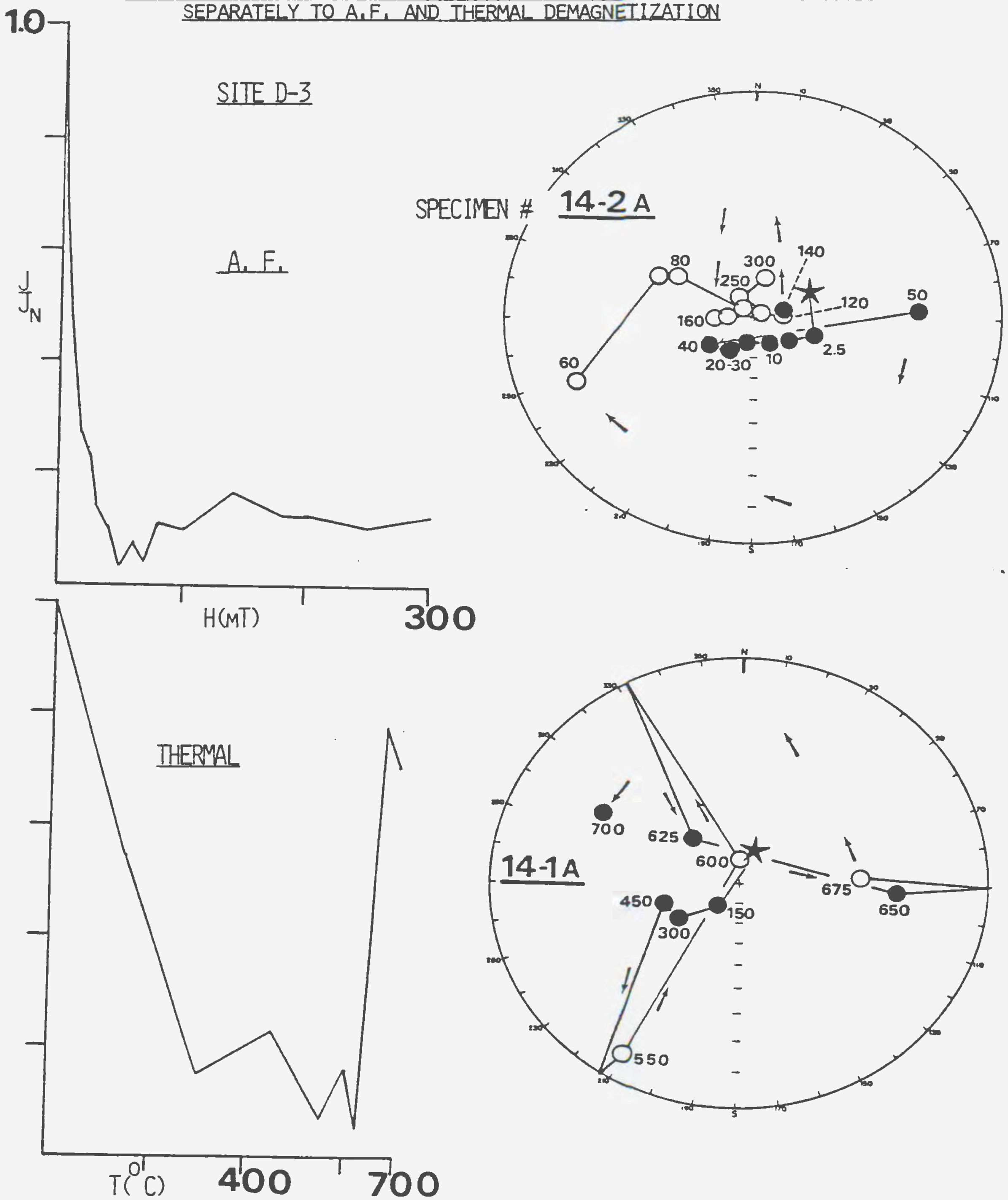


FIGURE 4-6 CONTINUED

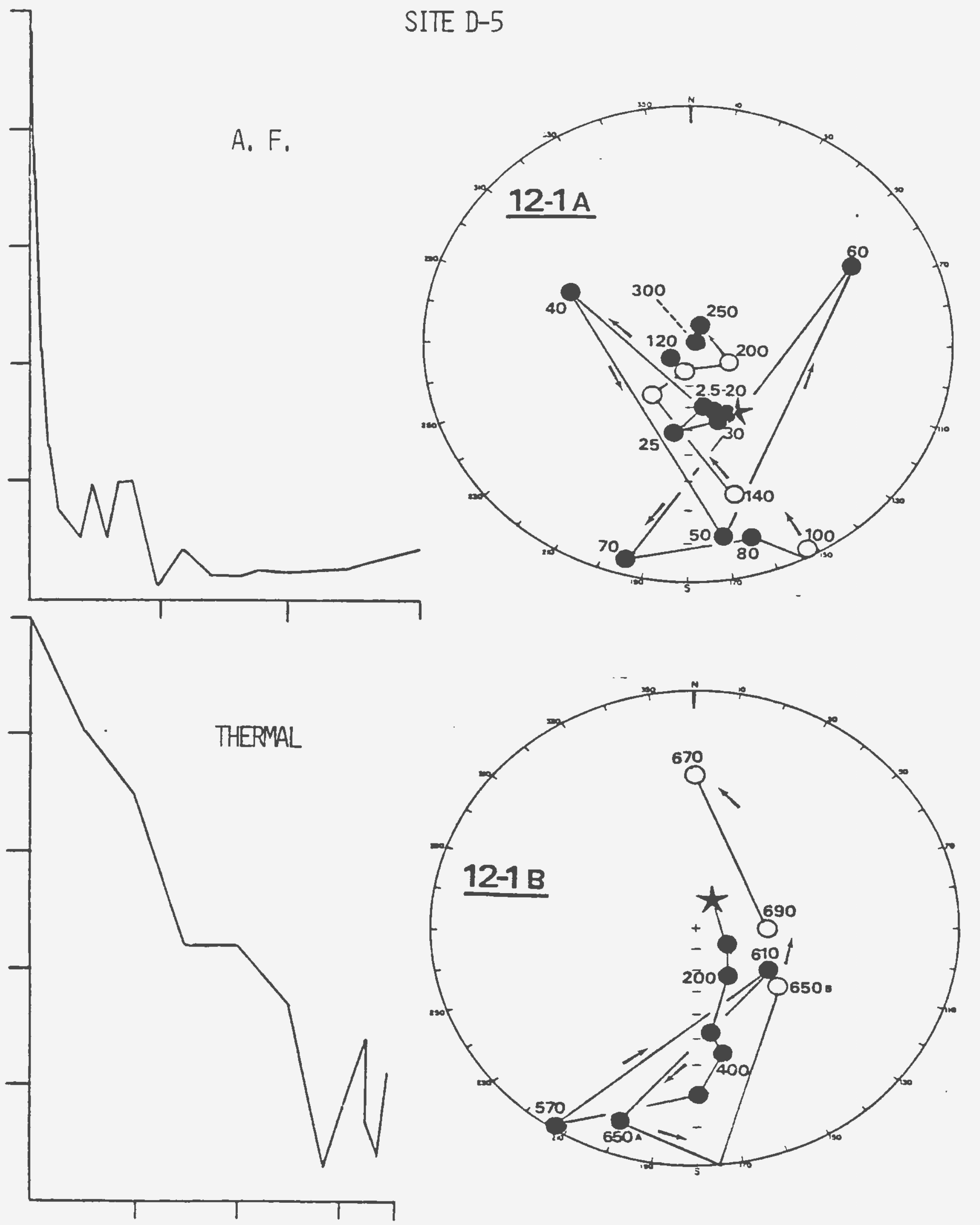


FIGURE 4-6 CONTINUED

SITE D-7

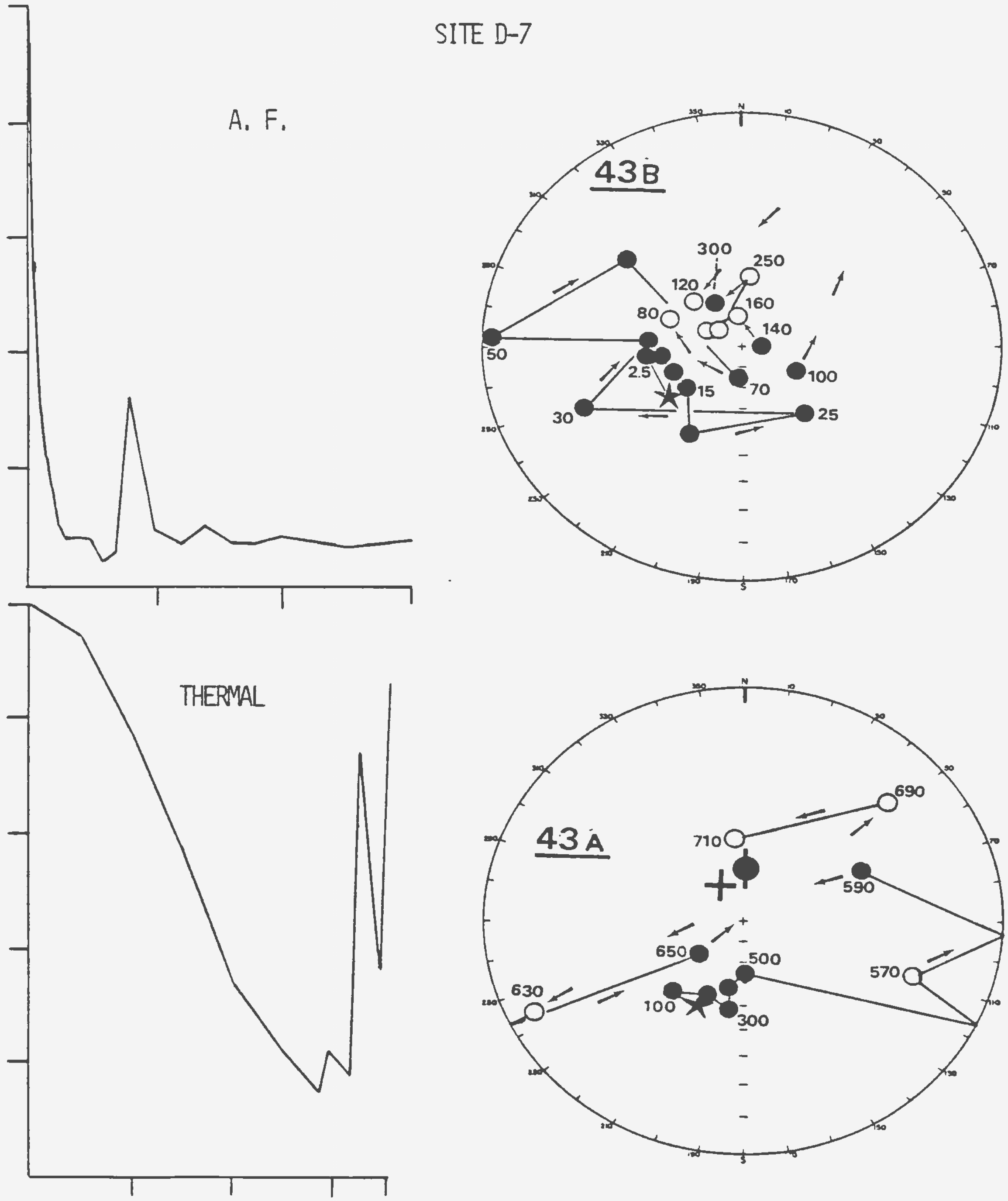


FIGURE 4-6 CONTINUED

SITE D-19

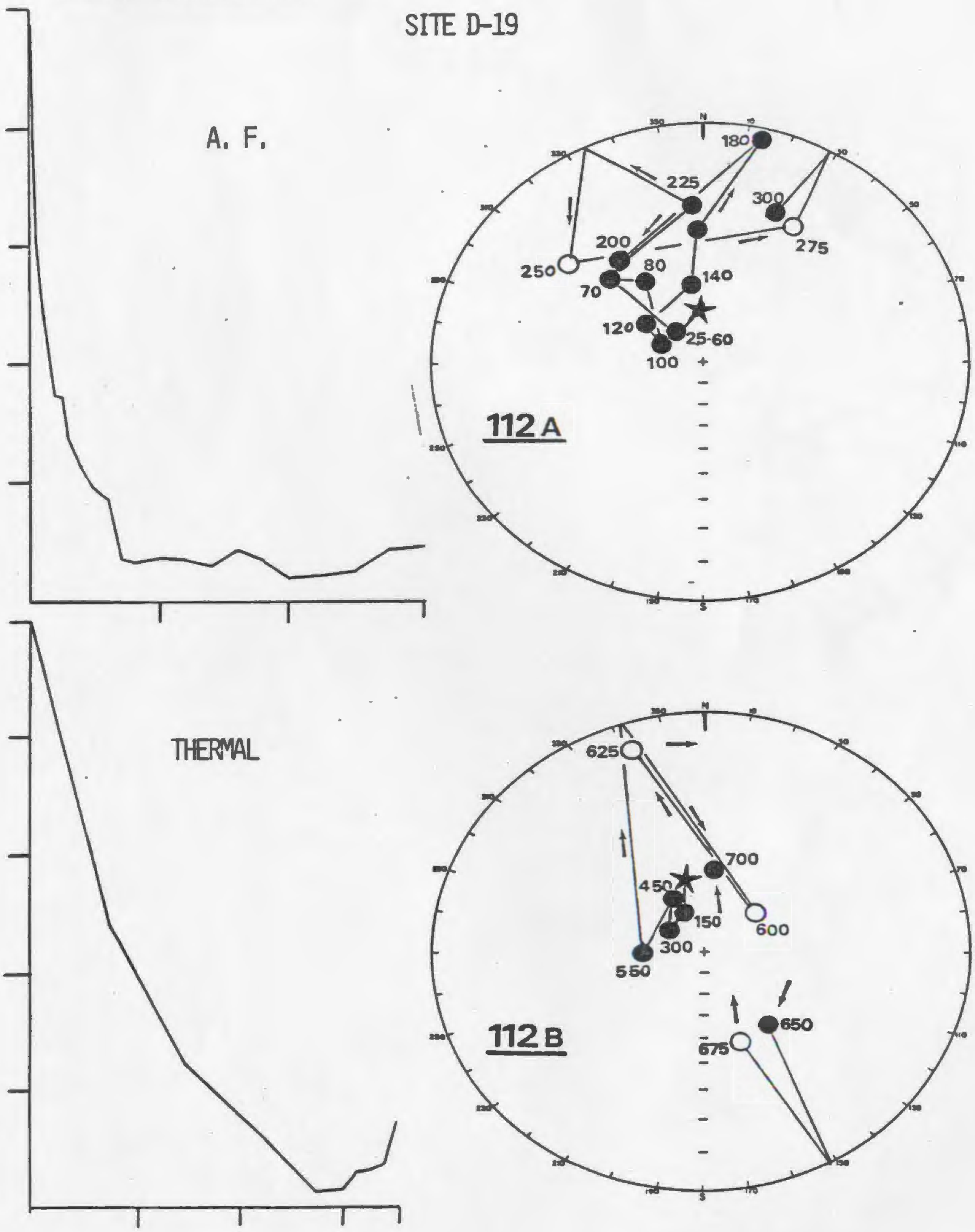
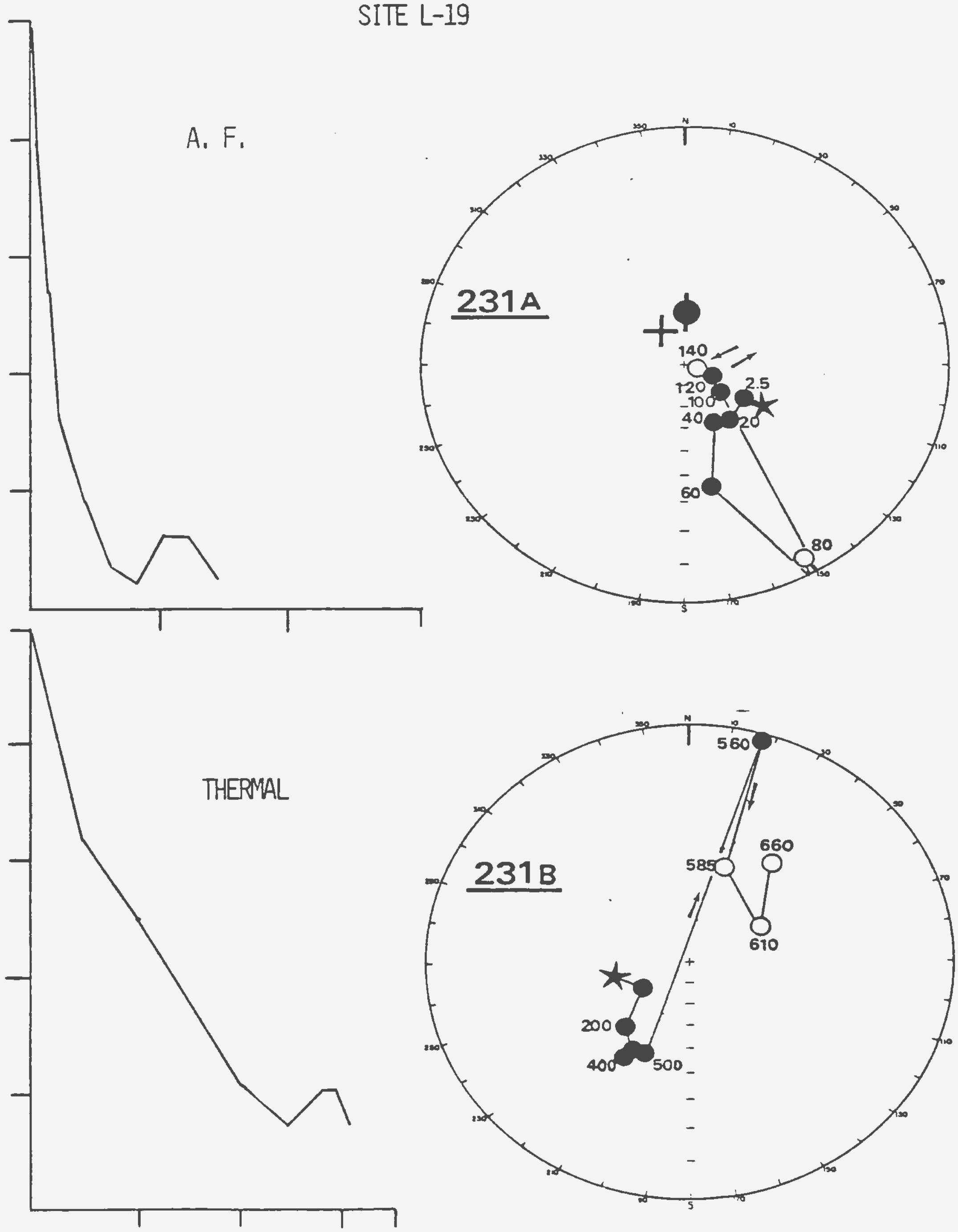


FIGURE 4-6 CONTINUED

SITE L-19



B L A N K

is shown by sample 231 in site L-19 which at best diverges by about 30°. Even this is quite reasonable for a heterogeneous rock where almost any degree of divergence of directions in different parts of a sample may be possible.

These results show that rock heterogeneity appears not to produce very serious dispersions of the measured directions from the paleomagnetic field at intermediate demagnetizing treatment, but introduces an error of about 10° to 20° on average. The fact that similar directions are obtained by different methods of treatment is encouraging evidence that a real paleomagnetic direction is being revealed.

4.6 Fold test

In thermal demagnetization it was observed in the between-site calculations that k was greater when all areas were included in the calculation than for Double Road Point alone, for most cleaning steps, implying a negative fold test. This did not hold true for the AF demagnetization and for thermal demagnetization at the 400° C and 500 °C steps.

A selection of this data is used in a fold test where the mean is calculated before and after the individual site mean directions are corrected for the tilt of the bedding plane (Table 4-8). The AF data includes Horizons 1,3,5,6, and 7 in area D, Horizon 20 in Area C, and Horizon 19 in Area L, with an average of two specimens (from two samples) per horizon, each of these having unit weight. In all cases k is about twice as great for uncorrected data as for corrected data, implying that the magnetization was acquired after folding. The same specimen population was present in all the AF steps but not in the thermal steps. For the thermal calculation each area has unit weight with the Area D mean the average of several horizon means and means from the 3 other areas from one horizon only. Again a negative fold test is revealed.

TABLE 4-9

Fold Test on Selected Pilot Demagnetization Data

Peak Field or Temperature	N	D	I	R	K	α_{95}
AF Study (random tumbler orientations)						
NRM	8	173	+85	7.108	7.8	21°
		124	+49	5.821	3.2	37
20 mT	8	239	+78	6.781	5.7	25
		140	+59	5.613	2.9	39
40 mT	8	215	+78	7.063	7.5	22
		138	+51	5.735	3.1	38
Thermal Study						
NRM	4	286	+77	3.955	66.0	11°
		148	+75	3.186	3.7	56
150°C	4	43	+89	3.905	31.5	17
		124	+65	3.182	3.7	56
300	4	233	+77	3.942	51.8	13
		162	+65	3.486	5.8	41
450	4	202	+78	3.703	10.1	30
		155	+62	3.472	5.7	42
545	4	245	+67	3.378	4.8	47
		195	+67	3.424	5.2	45
608	4	19	-37	.714	0.9	$\cos\alpha_{95} > 1$
		296	+33	1.453	1.2	$\cos\alpha_{95} > 1$

Upper value in each entry from directions uncorrected for bedding tilt.
Lower value in each entry from directions corrected for bedding tilt.

AF calculation uses six sites in Area D plus one site in each of Areas C and L each site having unit weight and ocrrected separately for tilt.
Thermal calculation uses a differing selection of sites at each step with at least four in Area D plus one each in Areas G, C, and L. Each area has unit weight with the Area D mean corrected for tilt using the average strike and dip from all 19 horizons in Area D.

CHAPTER 5

SINGLE-STEP DEMAGNETIZATION AND DETERMINATION OF POLE POSITION

5.1 Determination of optimum single-step treatment

It was decided that the single-step demagnetization of remaining speciments would be carried out by thermal treatment for several reasons: 1) Both the cause of the AF apparatus error, and its effect at low fields, are uncertain. 2) Similar precision in directions of between-site means were obtained by AF and thermal cleaning in the pilot study for most cleaning steps (Section 4.5-1). 3) Within most of the lower horizons closer grouping of sample magnetizations was obtained by thermal cleaning (Section 4.5.2).

It was decided that the optimum temperature for the single-step treatment would be determined by minimum dispersion. Even though the magnetization does not strictly show stable end points, appearance of these at high demagnetizing temperatures and fields is prevented only by masking of the dominant component of NRM by laboratory-induced remanence or randomly directed hard magnetization in heterogeneous features.

In Table 4-7 it can be seen that higher values of precision were obtained at temperatures of 300° C and lower, then above 300! C. Since thermal cleaning did not provide improved precision in the top horizon and it is probably different mineralogically from most of the lower horizons, the uppermost horizon was excluded from the single-step treatment. Also, this was restricted to Area D due to poor sampling characteristics in Area L and slumping in Area G. Since for the first few cleaning steps directions are usually similar, the optimum temperature for further cleaning may be determined by considering values of k.

The calculation for Area D only in Table 4-7 (b) includes 17 lower horizons plus the top horizon with a weight of only one out of nineteen, therefore this calculation should suffice in determining the optimum treatment temperature. Three groups of specimens are present: those heated in 100° intervals at lower temperatures (N = 15), those heated in intervals of 150° C or less (N = 4), and all those present in the thermal study, which were heated to 300°C and also calculated prior to heating (N = 18). In the largest group k is similar for the NRM and at 300° C. In the (N = 15) group k is similar, at 100° C and 200° C (and in both cases greater than for the NRM). In the smallest group k is similar at 150° C and 300° C and much greater than for the NRM. Judging by the two large groups of sites (N = 15, 18) the optimum appears to be at a temperature slightly greater than 200° C. Since the latter estimate carried very little weight with only 4 sites, the optimum single temperature for all 18 lower horizons would be slightly greater than 150° C. Since a number of specimens were already treated at 150° C, this is chosen as the best temperature for one-step cleaning of remaining specimens in the lower horizons of area D.

5.2 Procedure

The one-step thermal demagnetization was applied to 126 specimens in ten batches of 12 plus one batch of six, each batch equally divided between the top and middle shelves of the thermal demagnetization unit. In each batch half the specimens were placed upright and half upside down, and azimuthal orientations were random. Further details of the apparatus and procedure are the same as those described for the pilot thermal cleaning study described in Chapter 4.

The treatment was applied to one, or two, specimens per sample in the 18 lower horizons, depending on specimen availability. Some had only one specimen remaining after previous AF treatment, or previous thermal cleaning in 100° C steps not including the 150° C step.

Calculation of means included five specimens previously treated at 150° C, and was applied on three levels, like the calculation for the pilot study. First, sample means were taken for samples which included two specimens, then site means were calculated from 86 sample directions numbering from three to six in each of the 18 sites. Finally the between-site mean was calculated without correction for the tilt since it was established from the vector groupings that the magnetization was acquired after tilting of the beds (see Chapters 3 and 4).

5.3 Results:

5.3.1 Between-horizon means

The values of horizon means and the between-horizon mean with Fisher statistics are shown in Table 5-1 and Figure 5-1. These values may be compared with those obtained for the NRM (Tables 3-3 and 3-4) although the latter included a greater number of specimens in each sample.

The values obtained for the NRM between-horizon mean without tilt correction are D = 340°, I = +88°, R = 16.937, k = 16, α_{95} = 9°, for the same horizons as in this calculation. After cleaning at 150°C,

TABLE 5 - 1

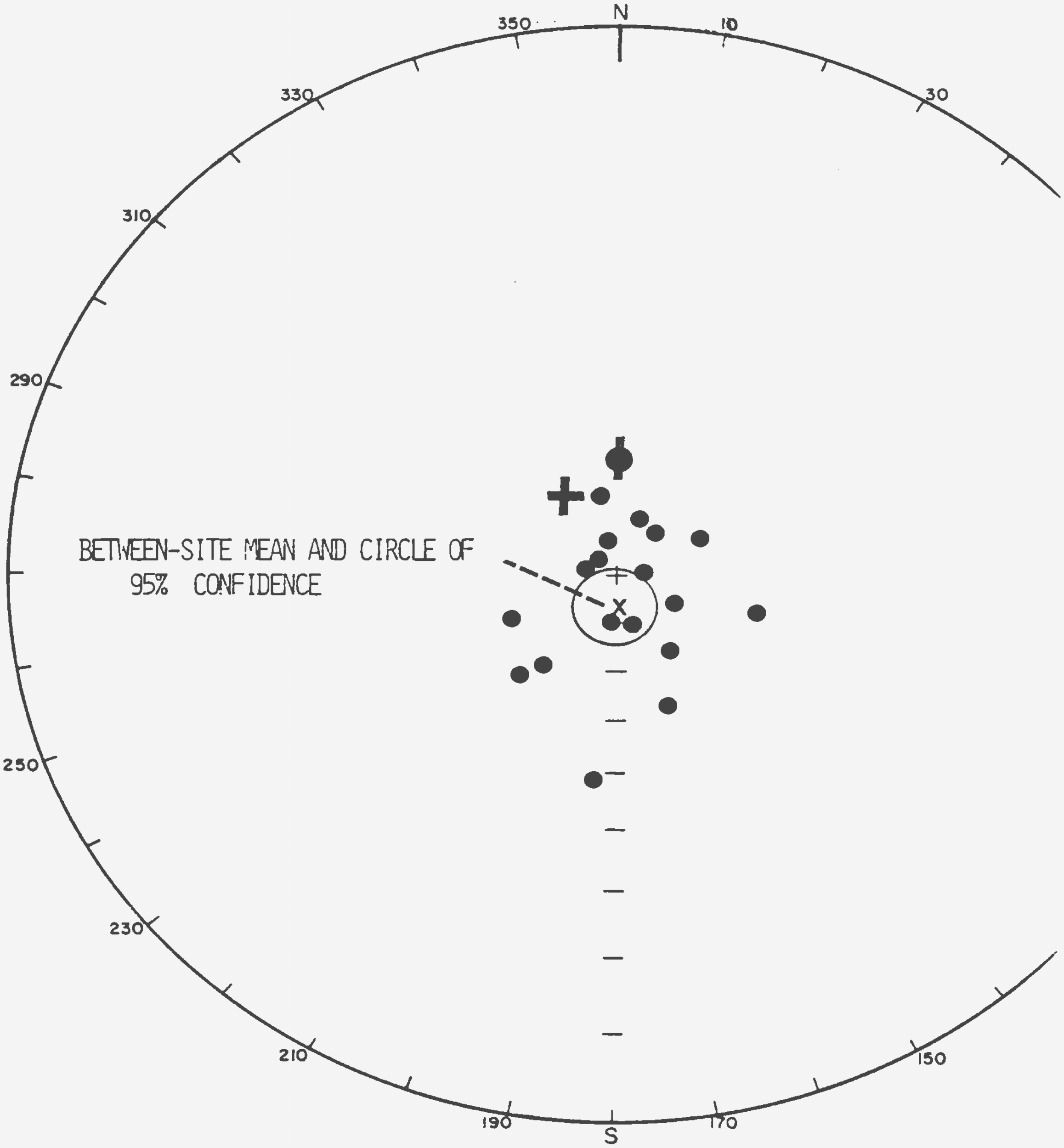
Single-step Cleaning: Horizon means and between-horizon Mean

Horizon	N	n	D	I	R	k	α_{95}
1	5	9	37	+79	4.556	9.0	27
2	4	8	219	63	3.817	16	23
3	5	9	347	72	4.434	7.0	31
4	4	6	18	77	3.583	7.2	37
5	5	10	113	78	4.077	4.3	42
6	3	6	168	79	2.736	7.6	48
7	4	7	185	49	3.65	8.6	33
8	5	8	159	62	4.105	4.5	41
9	6	9	306	85	5.800	25	14
10	4	5	244	68	3.720	11	29
11	5	8	182	80	4.320	5.9	34
12	5	9	217	67	4.721	14	21
13	3	9	148	72	2.87	15	33
14	4	6	107	63	3.547	6.6	39
15	5	8	338	83	4.046	4	42
16	4	8	65	74	3.61	7.7	35
17	3	5	284	84	2.30	2.9	93
18	3	6	86	85	2.84	12	36
Between-horizon	18		171	+84	17.118	19	8.1

N = number of samples in horizon. n = number of specimens in horizon.

Means calculated using N directions.

FIGURE 5-1 : SITE MEANS AND BETWEEN-SITE MEAN AFTER THERMAL DEMAGNETIZATION TO 150 °C



k increases to 19 and the mean direction moves southeastward by 8° almost directly away from the present (1977) field direction (D = 333°, I - +70°) and dipole field direction (D = 0°, I = +65°). This may reflect removal of a soft component along the present and/or dipole fields, although the influence of this component is not major since demagnetization to higher fields and temperatures did not reveal a continuous trend away from the present field direction. The plot of horizon means in addition reveals a distribution of points that is close to being Fisherian (Fisher, 1953) (random in azimuth and approximately Gaussian in angle subtended to mean), reflecting random errors, rather than a smear type of distribution. The latter would imply the presence of two components nearly equal in intensity but different in direction and necessitate further procedures to remove the softer of the two. In any case, the error circles for the NRM and one-step means overlap considerably, therefore the directions are not significantly different at the 95% probability level and are probably representative of the same paleo-field direction.

5.3.2 Within-horizon means

These cannot be directly compared to the NRM calculation, which was applied to a much larger average number of specimens in each sample, although, in most cases, the same number of samples in each horizon. Horizons, 1, 2, 4, 12, 15 and 16, one-third of the total, show an increase in precision relative to the NRM and the others do not (Table 3-2), and there is great variation in the change in k with cleaning, from site to site. Of great importance is the appreciable variation in k among the horizons, which occurred also in the NRM, probably reflecting the contribution of primary sedimentary features to scatter, since rock heterogeneity shows great variation from one site to another.

5.3.3 Within-sample means

In Table 5-2 examples are provided of directions obtained for specimens in sites 9 and 15, which after thermal demagnetization displayed respectively a decrease and an increase in precision for the between-sample mean. In Horizon 9 the resultant, R, for each of those three specimens containing two specimens also decreases, like the site precision, with cleaning. Mean directions in each sample do not change significantly and the site mean is quite precise before and after cleaning, also changing little in direction. This site probably does not contain any very soft magnetization, and all specimens contain the same component.

In Horizon 15, each of the three samples containing two specimens show improved grouping, like the between-sample mean, with cleaning and sample directions change very little (10°). However, the averaged movement for the site is about 10° to the SE away from the earth's field, possibly reflecting removal of a minor soft component along the earth's field as well as very soft spurious components.

5.4 Calculation of the pole position

A North pole position has been calculated using the assumption that the between-horizon mean for the lower 18 horizons in area D represents the field direction averaged over several thousand years at this locality during acquisition of the magnetization, and produced by

TABLE 5-2

Single-step cleaning: examples of specimen directions and sample means

	Specimen Directions			Sample Means		
Sample	Specimen	D	I	D	I	R
Horizon 9						
65	A	277	+73	290	+77	1.991
	B	312	+80			
66	A	284	+81			
68	A	151	+58	78	+80	1.720
	B	4	+58			
69	A	69	+79			
72	A	44	+75	4	+73	1.964
	B	338	+66			
73	A	239	+63			
Horizon 15						
37	A	243	+34	190	+56	1.495
	B	126	+43			
78	A	323	+72			
79	A	347	+71	230	+64	1.611
	B	219	+30			
80	1	72	+57	77	+49	1.978
	2	80	+41			
81	A	349	+36			

a geocentric axial dipole. The pole position is 12° southeast of the sampling locality at 35° N latitude and 51° W longitude.

The circle of 95% confidence about the mean direction can be transformed into an oval of 95% confidence about the pole position. Unfortunately this transformation disfavours polar regions since the variation in geographic latitude relative to magnetic inclination is greatest at the poles. Here the error oval is nearly circular and approximately twice the angular radius of the circle of confidence about the mean direction: $\delta_p = \delta_m = 16°$.

CHAPTER 6

CARRIERS OF MAGNETIZATION

The rock magnetism experiments carried out were acquisition of isothermal remanent magnetization (IRM), study of saturation magnetization vs temperature (J_s -T), and observation of hysteresis loops and polished sections. The main purpose of these is to show the presence and nature of magnetic minerals in the rock unit in order to provide evidence, independent from the demagnetization studies, that a stable remanence can occur. Other objectives are to look for any correlation between demagnetization behaviour and magnetic mineral content, and to attempt to isolate the shallow southwesterly component occurring in a few specimens throughout the formation but mostly in the top horizon in Area L.

Table 6-1 shows the selection of specimens for the experiments and a summary of the results. As much as possible, specimens were chosen to be representative of different horizons and areas and to show variations within a sample, within sites,and between different areas within the uppermost horizon. Additionally specimens were chosen to be representative of different types of magnetic behaviour, with about half showing the southwest component and half other directions after demagnetization. In some cases hysteresis loops and polished sections were taken by splitting a specimen which was wholly subjected to an AF demagnetization study followed by an IRM test. The J_s -T tests were performed on rock chips from material adjacent to a corresponding specimen which was used in the thermal demagnetization study.

TABLE 6 - 1

Summary of Properties of Magnetic Constituents

Area	Hor.	Specimen (Polished) (Section)			Coercive Force ±2[1] 20° C -	190° C	Directional change toward SW During demag? ( )uncertain	Pilot Demagnetizaton Study: Median Demag. Field /Temp.	Pilot Demagnetizaton Study: Stability Limit Dir'n	Pilot Demagnetizaton Study: Decay Curve Min.
MAGNETIC TESTS			H_{cr} (mT)	50% saturating Field	Fresh	Spc.		Alternating Field		
D	3	165A(i)			14	12	No	11	unclear	unclear
	5	50-2A(ii)					(Yes)	6	40	50
		167-2A	50±10	70			(Yes)	12	30	40
	9	66B	50±30	unclear			No	13	40	30
	12	219-1	40±5	40			(Yes)	7	40	40
G	19	116B	70±3	100	18	14	Yes	10	40	60
F	19	229A(iii)	80±3	110	25	18	Yes	10	30	50
		231A	70±3	90			No	14	40	80
THERMAL TESTS			Tc±10	Decrease on Cooling		Pre-Heated Spec.		Thermal		
D	3	14-1A	615°C	40	24	25	(Yes)	175	450	unclear
	9	73B	550	40			No	240	500	590
	19	112B	600	50	20	20	(No)	150	550	550
		5-1A	560	85			Yes	200	550	600
F	19	231B(iv)	600	35			No	200	500	500
		Repeat	575	20						
		231B	625	25						
		233A	615	0			Yes	220	540	665

Polished Sections: (i) 165A: magnetite with some alteration to maghemite or hematite and exsolution of ilmenite as lamellae (ii) 50-2A very fine grains probably hematite (iii) 229A: grains of magnetite, hematite, magnetite containing diffuse hematite alteration. (iv) 231B: fine grains mostly, possibly all, hematite.

1 From hysteresis loops. Uncertainty due to inaccuracy in reading from oscilloscope.

2. Last cleaning step before directions vary sporadically between steps.

6.1 Polished Sections

Four polished sections were examined in detail at a magnification of x500, and brief descriptions are provided in Table 6-1. Magnetite and hematite both appeared to be present, with magnetite grains absent or not easily visible in two specimens. Distinction was difficult in fine-grained specimens where determination is probably not as definite. The volume proportion of ferromagnetic minerals was on the order of a fraction of one percent, in a matrix of silicates.

Pre-heating to 700° C appears to have no obvious visible effect on the magnetic constituents since T50-2A and T23aB appear quite similar. A small amount of probable magnemite was present in one specimen, T165A, which otherwise contained large grains of magnetite. This specimen showed low values of coercive force and an unusual smooth change in direction during demagnetization from steep downward to northeasterly and upward. Specimen T50-2A appeared to contain mainly fine-grained hematite but did not show exceptional stability during demagnetization, with a very low median demagnetizing field (MDF). These two specimens were not used in IRM and Js-T tests and their demagnetization plots are not shown in the thesis, but all other specimens discussed in this chapter have demagnetization plots shown in Figures 4-1, 4-2, and 4-6.

In the uppermost horizon only a slightly higher proportion of hematite to magnetite was apparent, in specimens T229A and T231B, but this difference may not be significant. There appears to be an absence of any strong correlation of magnetic constituents with colour and stability, implying that magnetite may be present in at least small amounts throughout the collection, possibly as sub-microscopic grains in some cases, such as specimens T50-2A and T231B. Magnetite has many times the saturation magnetization of hematite and thus may be the main determinant of magnetic properties even if an overwhelming amount of hematite appears to be present.

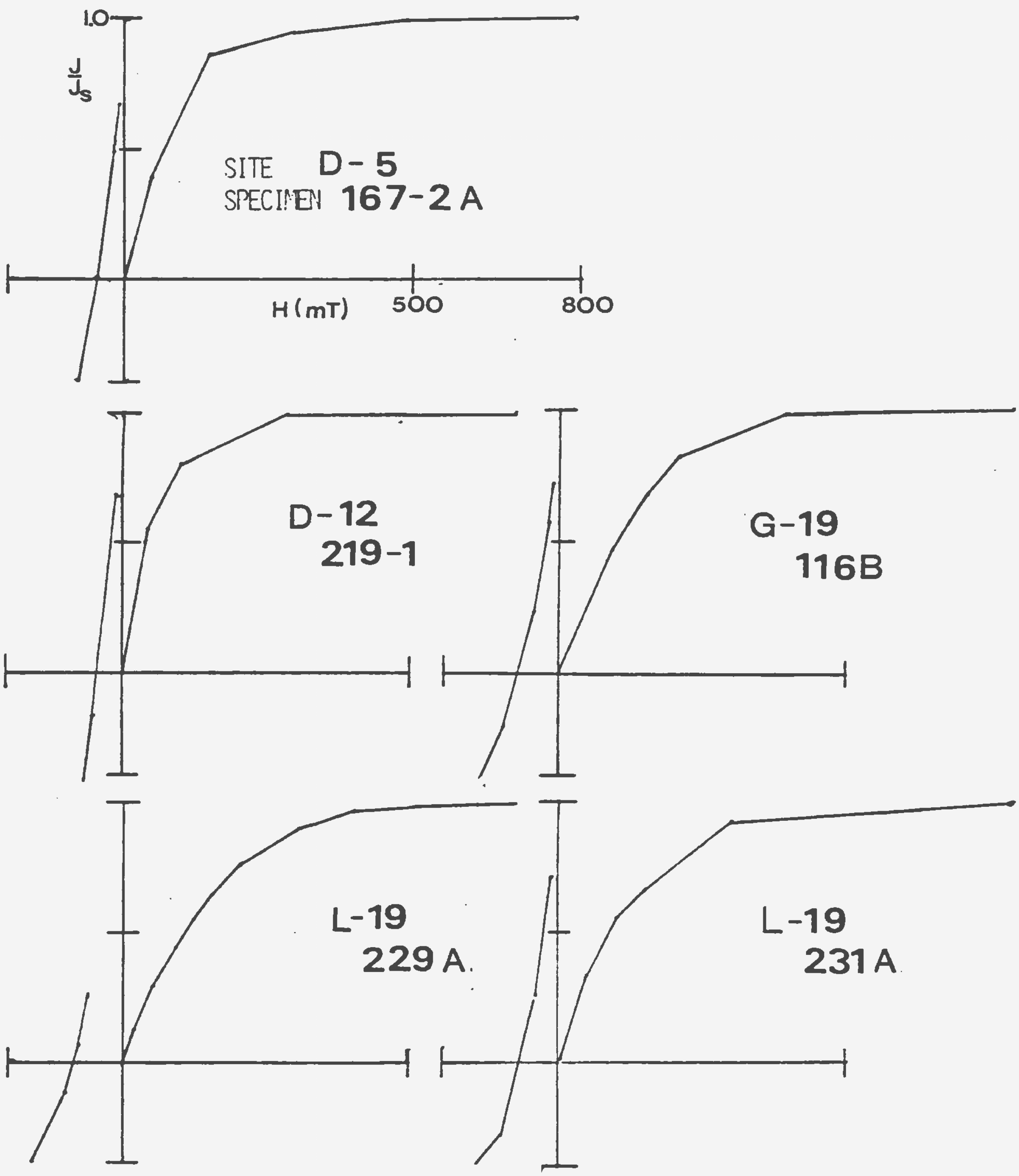
6.2 Acquisition of isothermal remanent magnetization

IRM curves are shown in Fig. 6-1 and values of coercivity of remanence (H_{cR}) and the field required to magnetize the specimen to 50% of the saturation remanence are shown in Table 6-1. These were obtained by subjecting a specimen to a DC magnetic field in increasing steps up to 800 mT, and after each step measuring the relative magnetic intensity with a Schonstedt Model SM-1 Heliflux Station Magnetometer. Six specimens which had previously been demagnetized in the AF Pilot Study, with corresponding demagnetization plots in Fig. 4-1, were treated in this study. One of these, T66B, was marginal in measurability during the IRM test and its IRM curve is not shown although an approximate value of H_{cR} is listed.

The intersection of the reversed-field curve with the horizontal axis gives the value of H_{cR}, which is a few times the bulk coercivity, the ratio depending on grain composition and shape. A good relative measure of the magnetic hardness is provided by both H_{cR} and the 50% saturating field (i.e. the field required to produce an intensity of remanence of one-half its saturation value).

The results of this test are compatible with the presence of a mixture of magnetite and hematite being present in most specimens, those

FIGURE 6-1 : ACQUISITION OF I.R.M.



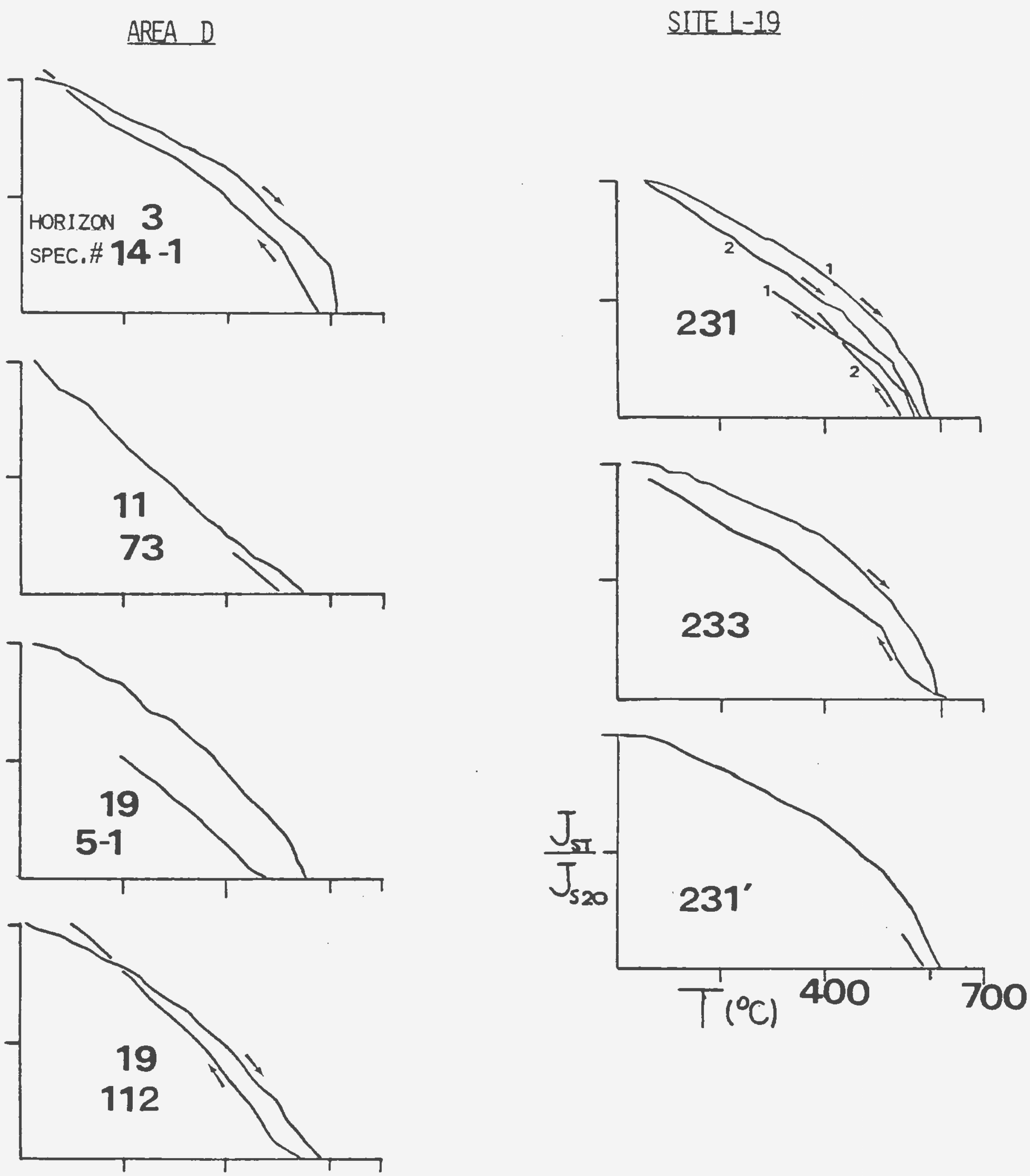
from the top horizon probably containing a higher proportion of hematite. This is in agreement with the mixture observed in the polished section of T229A which was subjected to an IRM test. No definite correlation of IRM test results with presence of the southwesterly component occurs, based on 4 tests on specimens carrying this component, and two on specimens not showing this component.

6.3 Variation of saturation magnetization with temperature

For the Js vs. T tests a vertical balance type of apparatus, designed originally by L.G. Kristjansson (Deutsch, Kristjansson, and May 1971) but with several modifications including an increase in the applied field, was used with specimens subjected to a saturating field of about 400 mT. The purpose of this test is mainly to find the Curie temperature of a sample, but also to find some indication of the blocking temperature distribution (similar to the curve of -dJs/dT) and vulnerability to heating in air, which in this case in enhanced compared to the effects of thermal demagnetization since a sample is finely divided for the test.

The test was performed on about 1 cm^2 of rock chips taken from the same cylinder, immediately above or below, a specimen on which a thermal demagnetization study had been made. Curves of Js vs. T are shown in Fig. 6-2 and results are listed in Table 6-1. The most important feature of these results is that no systematic variation is seen between the top and lower horizons, as in the IRM test. The tendency of a specimen to undergo an irreversible change of magnetic properties at high temperatures is shown by reversibility of the curve

FIGURE 6-2 : VARIATION OF SATURATION MAGNETIZATION WITH TEMPERATURE



during cooling, indicated in the table as the decrease of the Curie point in the cooling curve relative to the heating curve. Most of these specimens were irreversible to varying degrees. To make certain this was not due to sample temperature lagging thermometer temperature, one specimen (T23aB) was reheated, and the heating curve has a Curie Point close to the previous cooling curve and also has a similar lowering of the Curie Point during cooling. Assuming that most chemical change occurs near and above the Curie Point, it appears that about 5° of temperature lag may occur, and the rest of the Curie Point's depression is due to irreversible change.

6.4 Hysteresis loops

Hysteresis loops in a 120 mT alternating field were observed at room temperature and slightly above -196° C (boiling point of nitrogen) in five specimens, two of which had been previously heated to 700° C during thermal demagnetization. The apparatus used is similar to that described by Likhite et al (1965).

Values of bulk coercivity are about one-quarter the values of H_{cR} in the fresh specimens suggesting the presence of small (5-10μ) magnetite grains. Perhaps more likely is the occurrence of cation-deficient magnetite, especially in the light of other evidence: in the three fresh specimens hysteresis loops showed narrowing at -190° C. This is not very commong for most magnetic minerals, including magnetite, which exhibit a widening loop at low temperature (Morrish and Watt, 1958). According to Radhakrishnamurti and Deutsch (1974) such narrowing of hysteresis loops at low temperatures may reflect the presence of magnetite in a highly cation-deficient state, or of maghemite, and the fact that values of H_{cR} in specimens T116B and T229A are very high for magnetite may constitute supporting evidence for this. However, some uncertainty is here introduced by sensitivity of the measurement to position of the specimen in the magnet gap; but the observation is supported by the presence of narrowing in all three fresh specimens tested.

On average it appears that coercivity is greater in specimens that were previously heated reflecting the occurrence of irreversible change due to heating, also observed in the Js vs. T tests.

6.5 Summary

To summarize, both magnetite and hematite appear to be present in the coll-ction but magnetite dominates the magnetic properties due to its much greater intensity of magnetization. The smoothness of the Js -T curves is compatible with the presence of one magnetic mineral type with a single Curie temperature rather than two or more types of magnetic mineral with difference Curie tempeatures. Values of coercive forces and coercivities of remanence indicate that the magnetite grains are either very small, or cation-deficient, or possibly both. In addition the nearly linear thermal demagnetization decay curves indicate a very broad size range.

There is no obvious correlation between demagnetization behaviour and the results of these tests, although no incompatibility occurs. The alternating field required to completely erase the remanence varies from a value as great as the coercivity of remanence down to about half this value, suggesting that in some specimens, and particularly those from the top horizon, the harder carriers of magnetization either do not carry a stable component of magnetization or else are hidden by very unstable components possibly acquired during the experimental procedure. The temperature required to erase the stable remanence varies from very near the Curie temperature to about 150° below the Curie temperature. This indicates that the magnetic phases with high Curie temperatures either do not preserve a stable component, or else this is masked by laboratory-induced components due to the small proportion of heat-resistant phases, or chemical change occurs during heating. Values of Qn (Table 3-5) are too uniform to be useful for correlation with other properties, and a brief check shows that there is no obvious correlation with the presence or absence of the southwesterly direction.

It is not possible to correlate its presence in specimens with their magnetic properties. No other means of grouping these specimens exists since every site containing specimens having the southwesterly direction also contains specimens magnetized in other directions. Also, this direction was revealed at different cleaning levels in different specimens. It is possible only to state that a component of magnetization in a shallow southwesterly direction perhaps representing a paleomagnetic field direction and possibly of primary origin may exist, and is observed with certainty only in a small number of specimens.

CHAPTER 7

DISCUSSION AND CONCLUSION

7.1 Timing of Acquisition of NRM

The most important point to consider in concluding this study is the time when the dominant secondary magnetization in the Gaskiers Formation was acquired. The probable age of the magnetization may be inferred from what is known about the deformations the area was subjected to, discussed in Chapter 2, and from recent radiometric dating studies in eastern Newfoundland. Later in the chapter the dispersions found in directions of magnetization may be related to the proposed origin of magnetization and the pole position may be compared with pole positions found in other studies.

The secondary magnetization was likely acquired after the open folds were formed in the region as implied by the negative fold test, probably during the Acadian orogeny in the Devonian period. There is a less likely possibility that the folding occurred in the late Precambrian. In either case major heating occurred during the Acadian and any heating episode associated with Precambrian deformation was no more severe. (Papezik, personal communication). There is no evidence of retrograde metamorphism which, if present, could mask heating episodes prior to and more intense than the Acadian.

A large portion of the Avalon Peninsula was subjected to sub-greenschist metamorphism mostly of the prehnite-pumpellyite grade and probably associated with the Acadian deformation (Papezik, 1974). Two radiometric studies by the Ar^{39} -Ar^{40} method support the view of a major heating episode in the Devonian. Stukas (1977) studied samples collected from the Harbour Main and Bull Arm Formations and the Love Cove Group. The six samples closest to St. Mary's Bay giving clear results were taken over an area 60 km wide and ranging 60 to 90 km. distant from Double Road Point. Apparent ages taken from plagioclase concentrates at a release temperature of 880°C are as follows in decreasing order: 413 ± 6, 391 ± 10, 386 ± 10, 377 ± 3, 359 ± 4, and 356 ± 4 (revised by Reynolds, personal communication). Hussey (1979) reports Ar^{39} -Ar^{40} whole-rock dates ranging from 382 ± 5 to 391 ± 10 Ma from sericite schists from six samples collected from the Love Cove Group.

It should be asserted that these dates are secondary since primary ages in the area are considered to be much greater, as discussed in Chapter 2. They are most likely associated with the metamorphism of prehnite-pumpellyite grade, which results from temperatures between 200° C and 350° C and pressures between 1½ and 5 kb.

As discussed in Chapter 4 it was found that the dominant magnetization lost its stability at temperatures of 400° C to 500° C. The evidence suggests the presence of a viscous PTRM acquired at lower temperatures over along period of time (Briden, 1965). Destruction of remanence at 400° C to 500° C corresponds to heating for 10^6 years (typical duration of an orogenic episode) at temperatures of 250° C to 400° C for magnetite (and 150° C to 300° C for hematite) (Pullaiah et al, 1975). For magnetite, the likely carrier of the magnetization (see Chapter 6), this temperature range is only slightly higher than the allowable range according to the metamorphic grade, but these temperature windows are quite compatible, since there is a reasonable overlap.

It is possible that a secondary magnetization was imposed in an earlier orogenic period as a PTRM but this would have been almost entirely overprinted by the Acadian event.

Absence of an obvious high-temperature component allowable by the measured Curie points near 600° C (Chapter 6) must also be explained. This may be present in some specimens as the southwest component, as previously discussed. Lack of a systematic alignment of carriers of hard magnetization in most specimens may be explained by extreme heterogeneity of a primary origin. It is possible that large grain sizes did not allow a DRM to form during deposition. The more frequent appearance of the southwest component in the uppermost red mudstone layer may be associated with the red colouring, possibly indicating the presence of hematite carrying a CRM imposed prior to folding.

7.2 Sources of dispersion and the origin of NRM

At this point it is of value to consider dispersion in directions of magnetization on various tiers of the analysis as they relate to the origin of the magnetization. A very important factor in this discussion is heterogeneity, which refers to the presence of such features as dropstones or other large grains, possibly very strongly magnetized and having a direction of magnetization different from that recorded by a fine-grained matrix.

If the magnetization is primary heterogeneity will cause an increase in dispersion between specimens within a sample, with an unknown but possibly very large effect. Whether the magnetization is primary or secondary, inaccuracy of orientation of specimens relative to the sample will produce an error of two or three degrees. Within-sample dispersion was discussed in Sections 4.4.1.3 and 4.5.3 and the angle between specimen directions in a sample is generally ten to twenty degrees, which is greater than that expected from orientational inaccuracy alone. But the fold test showed that the magnetization is secondary and therefore the magnetization should be uniform, since dropstones and other clasts should be remagnetized in the same direction as the matrix, due to heating in amagnetic field. This contradiction can be easily explained by the presence of a very poorly aligned primary magnetization with blocking temperatures mostly above 500° C underlying the secondary magnetization. This could cause the within-sample error observed but not influence greatly the overall direction of magnetization due to low intensity, and scatter. The presence of randomly directed primary components with high blocking temperature is quite likely in the Gaskiers Formation since subaerial volcanic deposition took place (Chapter 2). Magnetite in this volcanic debris would be very fine-grained due to fast cooling and thus carry a hard magnetization which would not be aligned in direction in the case of large clasts, such as air-fall bombs.

Dispersion between samples within a horizon contains some of the within-sample error, since only one specimen was available from some samples. Dispersion due to slumping or other contortions of beds is not expected since the magnetization is secondary. An artificial source of dispersion is inaccuracy in orientation of samples, amounting to two to five degrees. These errors were discussed in Chapter 5 and are illustrated in Table 5-1 (p97) The precision parameter k is slightly larger than expected from orientational accuracy, due to the influence of within-sample errors (discussed above). The variation of k from horizon to horizon is fairly small, and compatible with the contention that the magnetization is secondary. The slight variation that does appear may be due to the small underlying scattered primary component present as a differing proportion of the total magnetization from horizon to horizon.

Dispersion in the between-horizon mean should be small since few sources of error are present if the magnetization is secondary. The paleosecular variation and inaccuracy of strike and dip measurements should not contribute to dispersion as they do to a primary magnetization. It is possible, however, for time differences to appear if differential cooling occurred at the close of orogeny, but this is unlikely on a scale of less than a kilometer. Even with uniform cooling, magnetization can be acquired at different times due to variation of blocking temperatures but these did not vary to a large degree, as was shown in Chapter 6. The dispersion observed here is probably due to error in site means, which is indicated by the circles of 95% confidence. The only other possible source of error is very recent relative movements between sites but it is not likely that any force large enough to cause this distortion has been present since the Acadian orogeny.

The final tier of analysis to consider is comparison with other rock units, and here the error in the overall between-site mean must be considered.

The only natural cause of error here must act in the same direction from site to site. Inclination error or other errors associated with deposition will do this within one area, but these will not be a factor since the magnetization is secondary. Recent large-scale rotation of the entire area would also have this effect but this is not likely to have occurred since the Acadian (see Chapter 2).

It appears that there is no systematic error in the overall mean, and only random errors are likely to be present, probably distributed symmetrically in a Fisherian way. The question that must be asked is: Does the 95% circle of confidence with a radius of 8° really represent accuracy of the between-site mean? There is probably no satisfactory answer to this question since there is no source of between-site dispersion which is not also present within sites. An alternative way of calculating the overall mean would be to give samples, rather than sites, unit weight. But this method would cause an underestimate of the radius of the circle of confidence since N would be 86 instead of 18, and inclusion of within-sample errors in the between-site mean cannot really be justified. Therefore the method used for calculating between-site Fisher statistics must be accepted even though it is unsatisfactory in some ways. In any case it may be justified intuitively that sites of an extent smaller than their separations (in most cases) should be considered as a unit in calculation of the overall mean, since random errors of an unknown nature may occur in the individual site mean directions. Errors on the smaller scale of an individual site are expe-ted to have a different cause, and would be separated from between-site errors by this method.

7.3 Comparison with other pole positions of similar age

Fig. 7-1 shows pole positions for this study and other Devonian poles from the northern Appalachians plus two poles from interior North America. The pole or antipole is plotted depending on which is closer to the Gaskiers Formation pole. This data is listed in Table 7-1. Pole PIV is from west of the Appalachians orogen geologically speaking but is considered by Brown (1978) to be from the mobile part of the Appalachians due to the displacement of the pole.

Poles CL, CRB, and BB are from the stable part of North America near the beginning of the well-delineated apparent polar wander (APW) path for North America from Carboniferous to present, and thus are here plotted as south poles. (Irving (1979) provides an excellent discussion of all paleomagnetic data from North America including tectonic implications). All other poles in Fig. 6-1 are from the northern Appalachian region. Partly due to lack of suitable rock units, mid-Paleozoic data from the southern Appalachians is lacking. Pole LRD is from a secondary magnetization of unknown age from the Long Range Dikes in western Newfoundland. Results of this study are very scattered (α_{95} = 16°) but the pole position is included due to proximity to the GF pole, which might possibly suggest that the LRD magnetization was imposed during the Acadian orogeny also. In addition, Wanless (1966) reports an age of 334 Ma. for the Long Range Dikes even though the time of their emplacement is late Precambrian.

Irving (1979) and Kent and Opdyke (1978) suggested that northern

FIGURE 7-1 : DEVONIAN PALEOMAGNETIC POLES FROM NORTH AMERICA

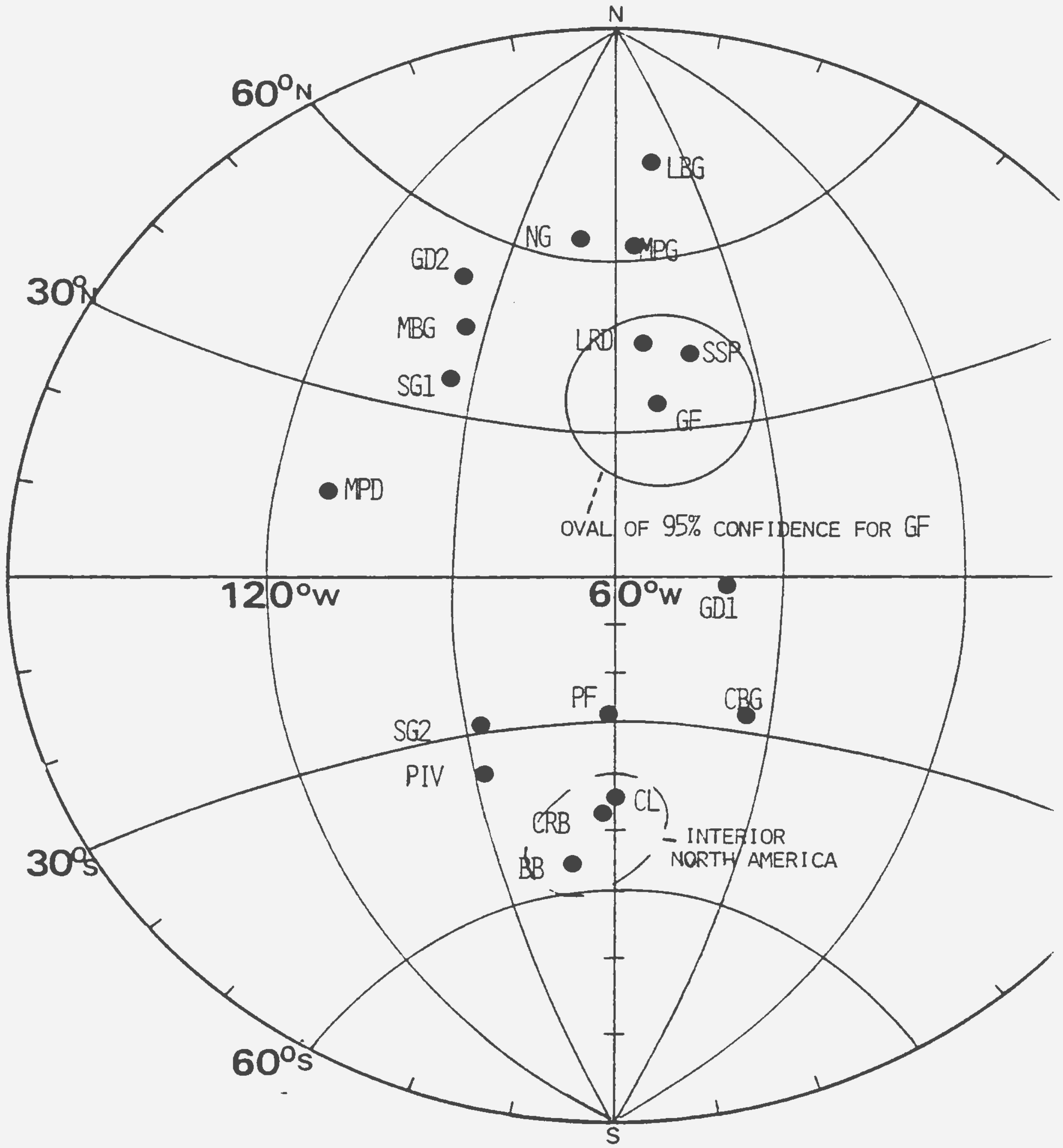


TABLE 7 - 1

Paleomagnetic Poles of Approximate Devonian Age From Northeastern North America

	Name	Sampling Location	Lat. (Degrees)	Long. (Degrees)	Reference
Northeastern Appalachians:					
GF	Gaskiers Formation	Nfld.	35N	51W	This study
GD1	Gander Zone Dikes 1	Nfld.	25N	39W	Murthy
MBG	Middle Brook Granite	Nfld.	47N	94W	(personal
GD2	Gander Zone 2	Nfld.	54N	100W	communication)
NG	Newport Granite	Nfld.	64N	71W	
LBG	Lockers Bay Granite	Nfld.	74N	46W	
LRD	Long Range Dikes	Nfld.	46N	54W	Pullaiah et al (1979)
MPD	Mount Peyton (diorite)	Nfld.	15N	112W	Lapointe
MPG	Mount Peyton (granite)	Nfld.	63N	55W	(1979)
CBG	Clam Bank Group	Nfld.	28S	34W	Black(1964)
SSP	St. Stephen pluton	N. Bruns.	43N	44W	Roy et al
SG1	St. Georges pluton 1	N. Bruns.	38N	95W	(1978)
SG2	St Georges pluton 2	N. Bruns.	29S	87W	
PF	Perry Formation (combined)	N.B.-Maine	29S	61W	Robertson et al (1968)
PIV	Presque Isle Volcanics	Maine	38S	88W	Brown (1978)
Interior North America:					
CRB	Catskill Red Beds	New York	47S	63W	Kent, Opdyke (1978)
CL	Columbus Limestone	Ohio	45S	60W	Martin (1975)
BB	Bekker Butte	Arizona	56S	71W	Elston, Bressler (1977)

Appalachia was south of its present position relative to North America in the Devonian and moved mainly by strike-slip displacement into its present position by the late Carboniferous. This explains the general trend of the data, although the displacement required is very large, since the mean Devonian position from the orogen lies well northward of the mean for stable North America. But the large amount of scatter between pole positions suggests that the situation is very complex either in terms of plate tectonic models or in terms of the underlying assumptions of paleomagnetism. It is possible that during part of the Devonian large non-dipole components were present in the earth's field, or very fast polar wander occurred, but this would affect both regions similarly. Most of the mid-Paleozoic paleomagnetic data is contradicted by the conclusion of Williams (1979) that relative plate-tectonic motion after the Ordovidian is not evident, and by the result of Kirschvink (1979) that an Ordovician pole position from the southwestern-most Avalon platform agrees with central North American data.

Apart from scatter in the pole positions, another problem exists concerning the island of Newfoundland as discussed in Chapter 1. Deutsch and Rao (1977) argued that western Newfoundland was in its present position relative to North America from Grenville time until the Ordovician. For this period eastern Newfoundland reveals a much different pole position than western Newfoundland. But large disagreement between the Devonian pole position for stable North America and Devonian pole positions from eastern, central, and western Newfoundland, which are themselves somewhat in agreement, suggests that all of Newfoundland was displaced from North America in the Devonian. At least the LRD pole is contradictory to the result of Deutsch and Rao (1977), but its proximity to the GF pole is rather compelling and suggests that the island was an integral unit in the Devonian. It is possible that this proximity is fortuitous, since the large error ovals about GF (16°) and LRD (35°) allow a 51° separation with a probability of 5%. Otherwise the data would imply that western Newfoundland had separated from the mainland before the Devonian and subsequently returned to its former position after the Devonian. The true LRD pole should be near the mainland Devonian pole position within the accuracy of the determination of Deutsch and Rao (1977). In fact the true pole could be 35° closer to the mainland position and still be within the calculated 95% confidence circle. But then it would still be 55° from pole CL, the nearest mainland pole plotted, and thus there is only a small chance that the calculated LRD pole is an inaccurate result representative of the Devonian pole position for the mainland, but misplaced by statistical error. A possible way of reconciling the pole positions GF and LRD with the conclusion of Deutsch and Rao (1977) is that western Newfoundland was in two positions in the early and later Paleozoic which can be relatively rotated into each other in such a way that the pole positions from Newfoundland and the mainland used by Deutsch and Rao (1977) still coincide. A pivot point in the central Pacific (180° W, 0° lat.) could be the centre of rotation for a reasonable displacement of western Newfoundland after the Devonian without separating the Ordovician and earlier poles from the mainland poles, since this pivot point is as close to the pole positions used by Deutsch and Rao as it is to western Newfoundland. The two positions of western Newfoundland separated by this displacement may describe the location of the western platform relative to North America in the early and late Paleozoic, with an intervening period of large movements possibly involving collision with the eastern platform as well as relative strike-slip motion of the two platforms.

The GF pole and antipoles were compared with the APW paths from the Devonian to present from Europe, Africa, and South America as compiled by McElhinny (1973) by rotating the GF pole according to the Bullard (1965) fit for each pair of continents (not shown). In every case the separations were much greater than those allowable by paleomagnetic inaccuracy (~30°). This would suggest that the Avalon platform was not joined to any of these three continents in the configuration of the Bullard fit in the Devonian (or whenever the GF magnetization was acquired). There are no grounds for comparing the GF pole with APW paths earlier than the Devonian in this manner since the Bullard et al (1965) fit is only applicable to periods from the late Paleozoic to sometime in the Mesozoic.

7.4 Summary and Conclusion

The between-site mean direction of magnetization for the Gaskiers Formation is D = 171°, I = +84° calculated from directions of remanent magnetization, after demagnetization to 150° C, in 131 specimens from 86 samples from 18 sites in Area D. The corresponding paleomagnetic pole position relative to eastern Newfoundland at the close of the Acadian orogeny during the Devonian is 35° N latitude, 51° W longitude at an angular distance of 12° from the sampling locality.

Errors in this determination act randomly and thus the probability distribution of the true direction of magnetization is Fisherian. With the reservations discussed in Section 7.2 the angular radius of the circle of 95% confidence about the mean is 8° ($k = 19$) and the corresponding error oval about the pole position is nearly circular with an angular radius of 16°.

The magnetization is stable up to a temperature of between 400° C and 500° C and up to a peak alternating field of 40 to 50 mT. It was mostly acquired as a viscous pTRM during heating induced by the Acadian orogeny.

An underlying primary magnetization of low intensity occurs mainly in the 400° C to nearly 600° C blocking temperature range as a very scattered DRM possibly combined with a CRM. A small number of specimens mainly in the uppermost red mudstone layer possibly recorded this component with reasonable alignment as a very stable magnetization directed horizontally to the southwest. This data cannot be fold-tested due to proximity to the direction of strike, and because of some scatter. Due to its random nature the primary component is removed from the overall magnetization statistically in the final calculation, which involves only the lower horizons.

The Gaskiers pole position lies among the other Devonian pole positions from the northeastern Appalachians which are very much scattered, probably because of very fast apparent polar wander, or because of small-scale relative tectonic movements. The pole position would agree with interior North American results if the sampling locality had been displaced about 75° southward of its present position, relative to North America, when its magnetization was acquired. The sampling area could have been rotated about a nearby axis with little effect on the pole position since the pole position is very close to the sampling locality.

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APPENDIX

Fortran program used for application of Fisher statistics to Pilot study data. (The text of the actual program listing and printout of the detailed paleomagnetic data (total, 38 pages) has not been included with the main body of this thesis. A complete copy of this text may be obtained upon request to the Department of Physics, Memorial University of Newfoundland. Contents and a brief explanatory note follow below.)

Contents

Order of listing of data:

AF Thermal	1. initial calculation 2. array sorting 3. recalculations for comparison	(a) specimen direction (b) sample mean (c) horizon mean (d) between-horizon mean

Variable and array usages are explained within program listing.

If number of vectors in a mean is two, θ , the angle between the vectors is output rather than α_{95}.

"COS A 1" means that cos   was calculated as being greater than 1 and therefore α_{95} is undefined.

Units used in program are Oersted rather than mT. 10 Oersted = 1 mT. 1 Oersted in the AF listing and 20°C in the thermal listing indicate values of NRM.

The site numbering system in the listing is different from that in the text. Numbers corresponding to those in the text are added manually beside the site numbers (under the heading "HORIZON") in the printout for the AF and thermal NRM results.

Specimen, sample, and horizon numbers are the same as those in the laboratory except that consecutive alphanumeric specimen numbers are converted to consecutive numberals. The preceding numbers in partial parentheses are consecutive numbers assigned within each of the three tiers of analysis (the specimen tier was not used here although the program is capable of averaging specimen directions to obtain sample means).